GESP-236

FINAL ANALYSIS AND TEST REPORT

SPACECRAFT ATTITUDE CONTROL SYSTEM PROTOTYPE AND TEST

Contract No. 951895

NUCLEAR SYSTEMS PROGRAMS
SPACE SYSTEMS
GENERAL ELECTRIC
CINCINNATI, OHIO 45215

Prepared for
Jet Propulsion Laboratory
Pasadena, California

FINAL ANALYSIS AND TEST REPORT

SPACECRAFT ATTITUDE CONTROL SYSTEM PROTOTYPE AND TEST

July 1968

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NUCLEAR SYSTEMS PROGRAMS
MISSILE AND SPACE DIVISION
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I. ABSTRACT

This document is the final report on the design, development, fabrication, and test of a laboratory prototype, passive vaporizing liquid ammonia attitude control system. Performance tests have demonstrated the specified control and conceptual operation of a fully passive ammonia feed system coupled with attitude control thrusters. The system operates at spacecraft ambient temperatures and is composed of the following subsystems: liquid ammonia propellant storage tank with zero-g heat exchanger-vaproizer intimately brazed onto the exterior; liquid throttling valve; gas pressure regulation; solenoid mounted thrusters; and inline solenoid valve. The system was designed to meet the thrust level requirements (0.315 lb_f/nozzle) of a hypothetical spacecraft in the 14,000 slug-ft^2 class. The principal system feature is the passive zero-g feed system which draws the needed thermal energy for the latent heat of vaporization of the liquid ammonia from the liquid ammonia sensible heat and spacecraft waste heat.

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A. PROGRAM OBJECTIVE

The overall objective of this program was to design, fabricate, develop, and test one prototype passive vaporizing liquid ammonia (NH_3) system for ultimate application in spacecraft attitude control. The system was defined to be a laboratory prototype, functionally similar to flight hardware, but not totally optimized. It would consist of an integrated passive zero-g propellant storage tank and feed system with attitude control thrusters which would help solve the problems associated with its design and would advance the state of the art. The goal of the design was to utilize spacecraft waste heat to vaporize sufficient ammonia propellant to supply two thruster nozzles simultaneously, each nozzle generating 0.315 lb_f for up to 18.2 seconds. These performance parameters are applicable to a hypothetical spacecraft with a mass moment of inertia of 14,000 slug-ft^2, utilizing two thrusters to produce a moment couple upon the spacecraft to accomplish roll or pitch maneuvers. The goal of the testing effort was to obtain an ammonia gas flow rate of 6.3×10^{-3} lb/sec from the feed system, and demonstrate that the system concept works through the successful functioning of the components as an integrated attitude control system.

B. SYSTEM DESCRIPTION AND OPERATIONAL CONCEPT

The system concept under study incorporates in its design a heat exchanger-vaporizer for effective conversion of ammonia from a liquid to a gaseous state. The type of vaporizer selected is a single pass tubular heat exchanger (with associated throttle valve connected at the entrance) intimately brazed in a helical coil to the exterior surface of the propellant storage tank, as shown in Figure 1.

This type of heat exchanger-vaporizer provides a simple solution to the three major requirements for a liquid storage, gaseous feed ammonia propellant system: (1) furnishing the energy required to vaporize the ammonia, (2) designing an effective heat exchanger to transfer the heat of vaporization into the liquid, and (3) controlling the liquid-vapor interface in the storage tank at zero gravity.

The heat exchanger furnishes the energy required from two heat sources: the sensible heat of the fuel tank and liquid propellant, and the thermal radiation and conduction from spacecraft structure and

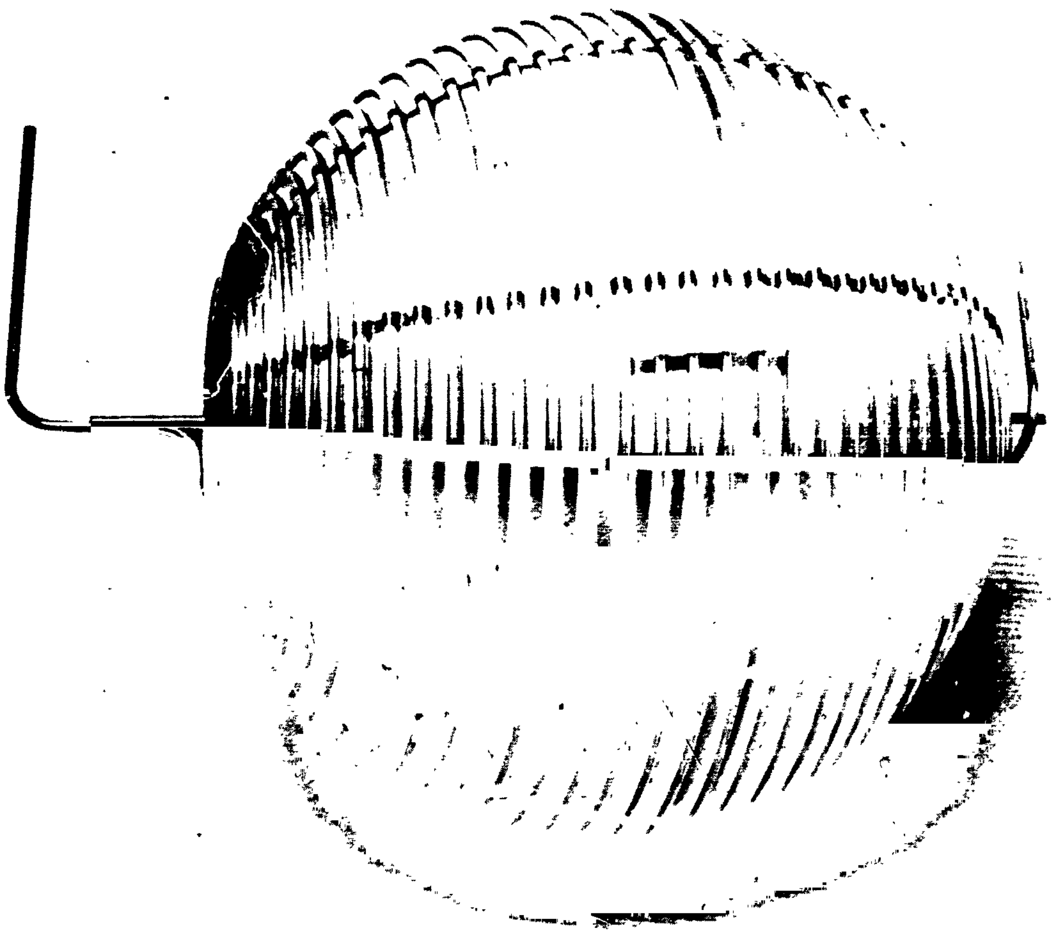


Figure 1. 18 Inch Propellant Tank with Heat Exchanger Brazed onto Exterior Surface. (Note Nichrome Strips Used to H_ld Heat Exchanger in Place During Brazing Operation).

electronics components.

The heat transfer is effectively accomplished in the helical coil by the very short thermal path accross the tank and tube walls, compared to the long flow path. During zero-g operation, since ammonia is a wetting liquid, the bulk of the inner surface of the tank will be in intimate contact with the liquid ammonia, and the sensible heat of the liquid will be readily available for transfer through the wall of the tank into the heat exchanger. After passing through the two phase throttling valve, any liquid in the heat exchanger will be driven to the wall by centrifugal force where vaporization will take place.

The heat exchanger approach to the solution of the zero-g storage problem can be described as follows:

Two solenoid valves, shown in Figure 2, are used to control propellant flow; the thruster solenoid valve, and a solenoid valve between the storage tank outlet and throttling valve. The two valves operate simultaneously so that there is always a dynamic fluid in the heat exchanger while thrusting. The key feature of this approach is the two-phase throttling valve at the inlet of the heat exchanger, which automatically adjusts its effective flow area to accommodate either liquid or vapor, while maintaining a constant pressure differential between the tank and the vaporizer whenever propellant is flowing. With this feature, it is irrelevant whether liquid or gaseous ammonia is extracted from the tank, and therefore control of the liquid-gas interface is unnecessary.

The solenoid valve between the tank and the throttling valve is actuated each time a thruster valve pair is turned on. Its function is to prevent flooding of the vaporizer during non-operative periods. Flooding can occur if there is a decrease in vehicle temperature, whereupon the vapor in the heat exchanger would condense and the throttling valve, in an effort to maintain the constant pressure differential between the tank and the heat exchanger, would permit more ammonia to enter the heat exchanger. The positive shutoff by the solenoid valve prevents this occurrence.

Automatic compensation for either liquid or vapor flow was mentioned above as one of the features of the two phase throttling valve. A second reason for the use of this valve is, of course, to provide proper thermodynamic throttling of the ammonia as a prerequisite for the ammonia entering the heat exchanger tubing. The throttle valve

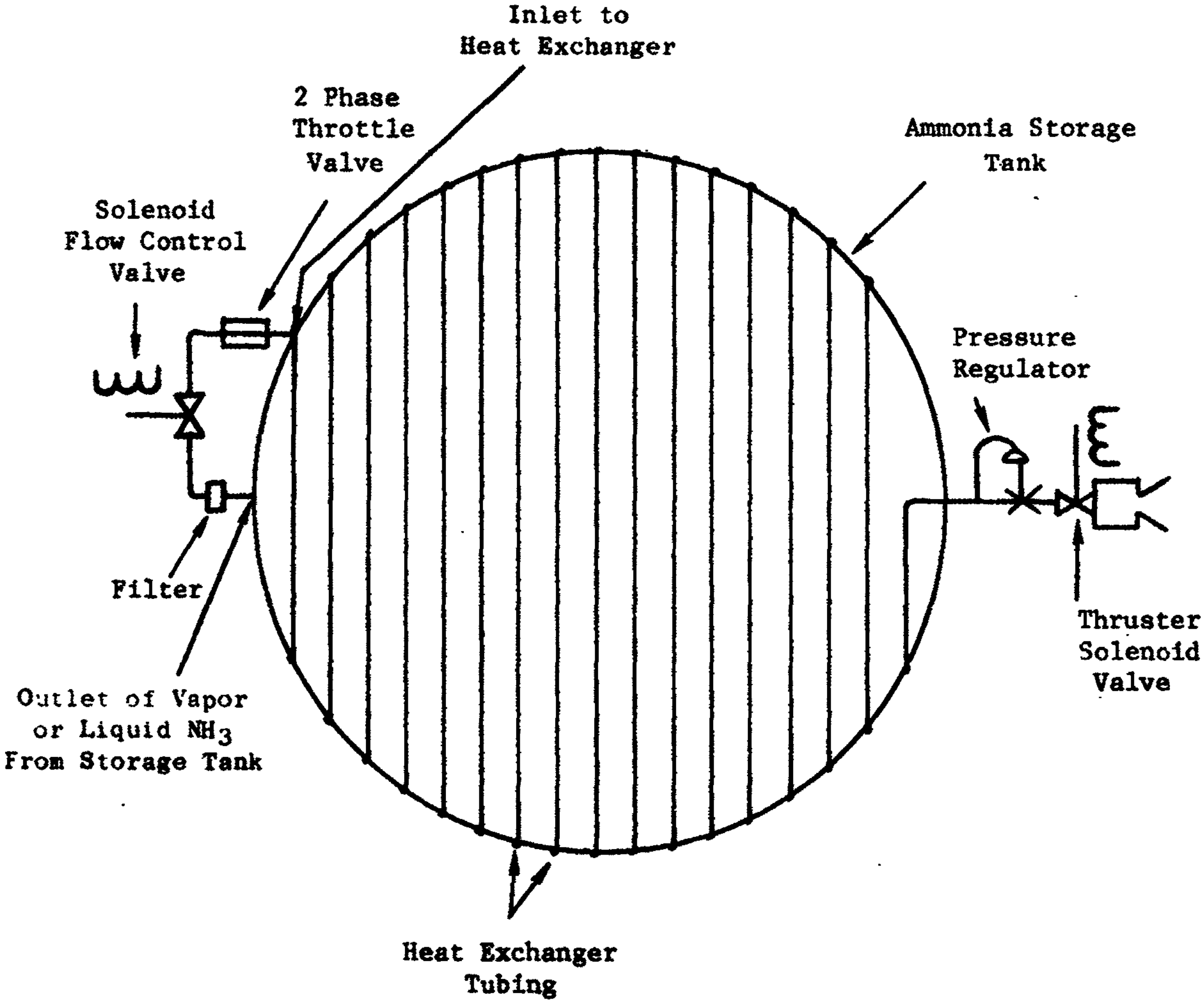


Figure 2. Ammonia Vaporizing Attitude Control System Flow Schematic.

produces a pressure differential during periods of propellant flow between the storage tank and the heat exchanger tubing. The pressure differential causes a corresponding saturation temperature differential to exist between the storage tank and the throttled ammonia. Hence a necessary temperature potential is established to initiate a heat transfer process, from the storage tank sensible heat and thermal radiation, to the ammonia in the heat exchanger tubing.

During the operation of this system, the storage tank temperature will diminish as heat is removed for vaporization. The system can continue to operate within a pressure time transient until the pressure in the storage tank, and hence the vaporizer output pressure, drops below an acceptable value for proper operation of the attitude control thrusters.

C. LABORATORY SYSTEM DESCRIPTION

There is only one major conceptual difference between the laboratory passive vaporizing ammonia system and a flight version. In the laboratory version, one solenoid valve is added (SV-2, Figure 3), which is used to control liquid ammonia tapped from the bottom of the storage tank. In the laboratory at one g, the best method of simulating either vapor or liquid effluent from the storage tank is to tap vapor from the storage tank ullage cavity via SV-1, and liquid via SV-2. During operation of the system, if the vapor feed mode is desired, SV-1 and SV-3 and 4 will be pulsed simultaneously; if the liquid feed mode is desired, SV-2 and SV-3 and 4 are pulsed simultaneously.

The general layout of components for the laboratory prototype attitude control system is given in Figure 4.

D. LABORATORY SYSTEM POST DESIGN

DESIGN REQUIREMENTS

1. Total impulse, 5800 lb_f-sec.
2. Thruster force level, 0.315 $lb_f \pm 20\%$
3. Nominal gas generation rate, 6.3×10^{-3} lb/sec.

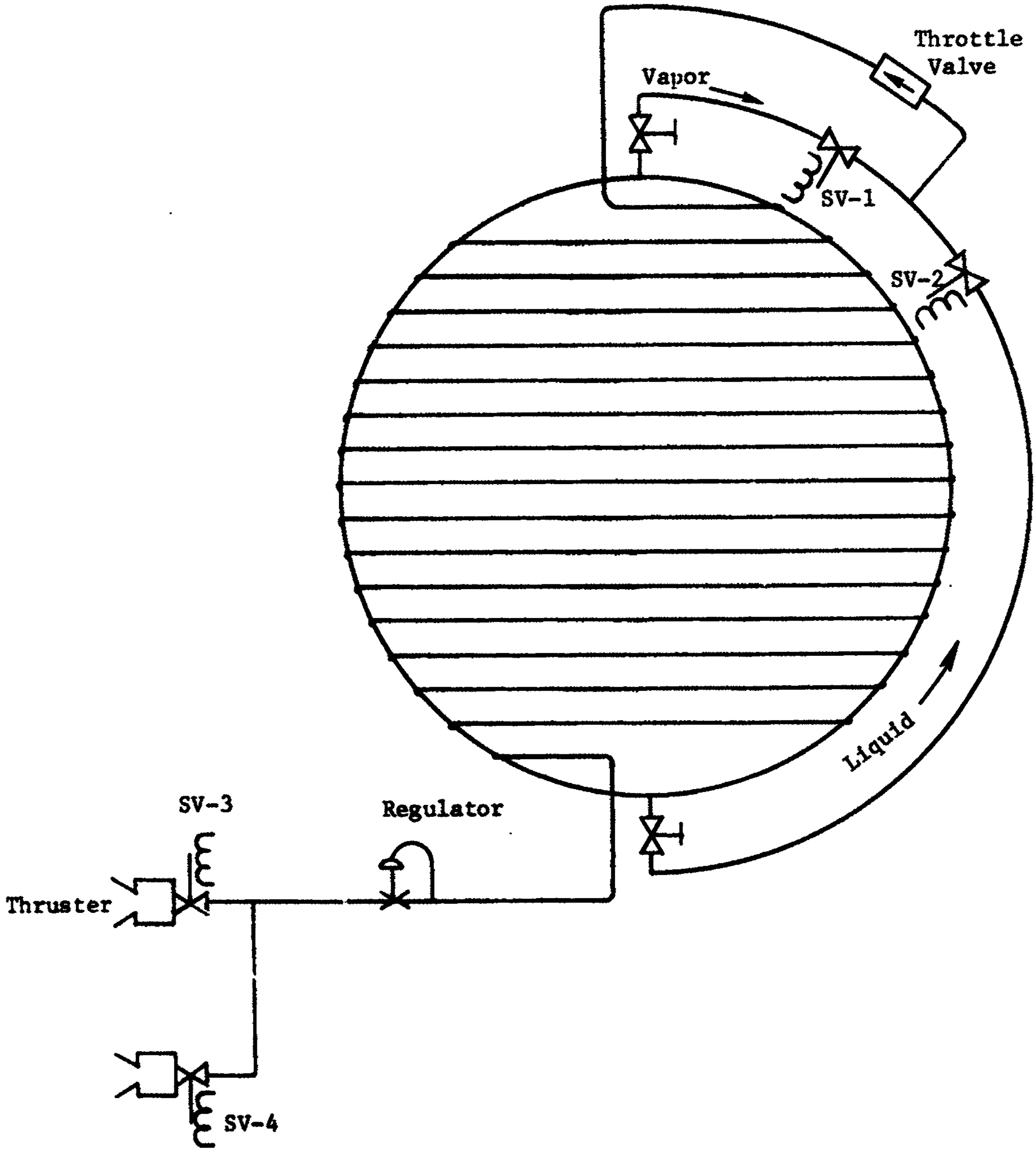


Figure 3. Laboratory Passive Vaporizing Ammonia System.

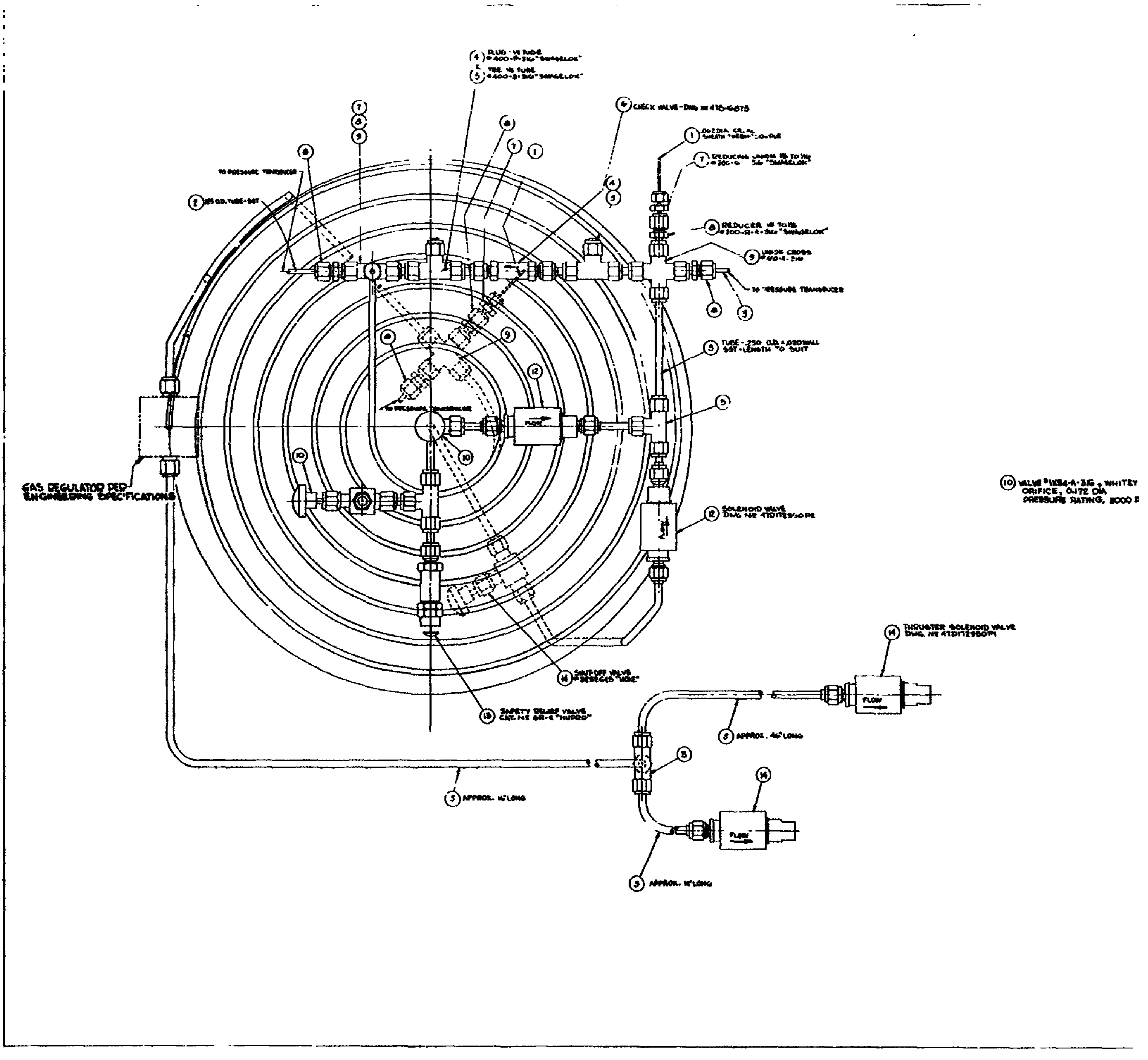
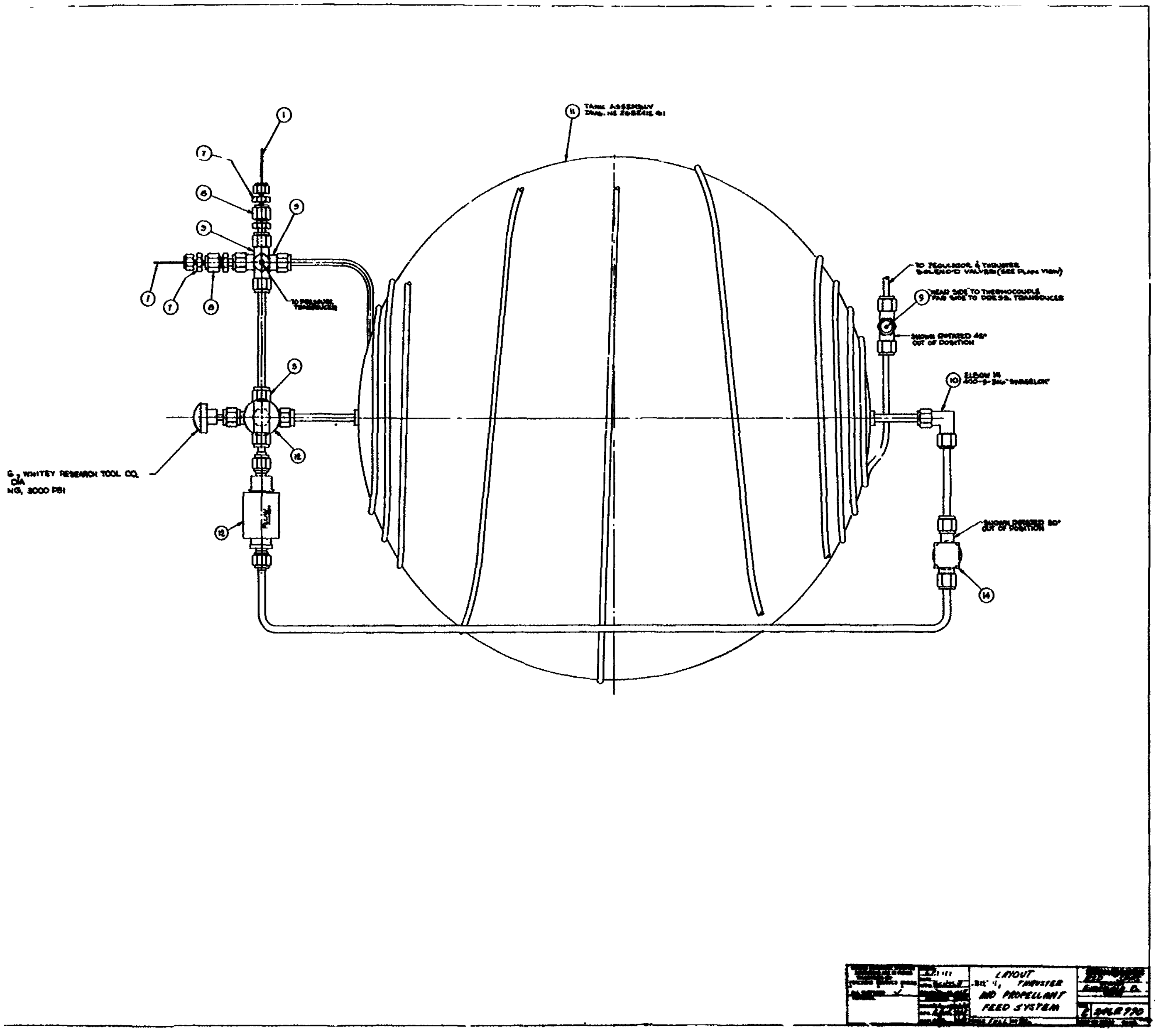


Figure 4. Prototype Feed

FOLDOUT FRAME



ed System Layout. (Dwg. #246R770)

FOLDOUT FRAME

COMPONENT DESIGN

Laboratory Storage Tank Design

Early in the program, type 6061-T6 aluminum, a likely candidate alloy for flight design, was considered for the laboratory prototype along with type 304 stainless steel. The main advantage of the use of aluminum was a closer approach to flight design, and an increased knowledge of the associated technology and problems. The advantages of stainless steel were simplicity of fabrication, lower cost, shorter lead time, and more reliable delivery date.

In order to demonstrate the concept with a minimum of extraneous problems, it was decided to go with stainless steel for the laboratory prototype. Since the flight design would not use a stainless steel alloy, the laboratory prototype tank was designed for laboratory testing only, based on the following assumptions:

a. Highest environmental use temperature in the GE laboratory - 85°F.

b. Highest internal use vapor pressure - 165 psia. Max temporary storage temperature - 120°F.

c. Tank to be mounted in a soft nylon support sling; therefore no local stress problems.

d. Material - 304 annealed stainless steel. Material strength: Sy = 30,000 psi minimum.

e. Safety factor - 1.5 based on 0.2% offset minimum yield of 304 SS annealed.

f. Specific impulse of ammonia gas at ambient temperature - 100 sec.

The most important functional similarity between the laboratory tank and flight hardware is heat transfer. Since the limiting thermal conductivity is that of the ammonia vapor in the heat exchanger and the ammonia liquid in the tank, it can be easily shown that the difference in thermal conductivity between aluminum and stainless steel does not significantly affect the overall heat transfer characteristics. The heat transfer coefficients for aluminum and stainless steel are 46.8×10^3 and 3.2×10^3 BTU/hr-ft^2-°F, respectively, while that of liquid ammonia is only 3.77×10^2BTU/hr-ft^2-°F. Assuming that the liquid film thickness is equal to the tank wall thickness, the overall heat transfer coefficients for the case of aluminum and stainless steel tanks differ by less than 10%. In the case of the heat exchanger, using the value of 1.73×10^2 for the heat transfer coefficient of the saturated ammonia vapor film, the overall heat transfer coefficient in the case of aluminum is 1.72×10^2 BTU/hr-ft^2°F compared to 1.64×10^2 BTU/hr-ft^2-°F for the stainless steel heat exchanger. This difference is less than 5%.

The tank volumetric capacity was first determined from a consideration of the total impulse requirement as follows:

a. Total Impulse = 5800 lb_f-sec.

b. Using a propellant specific impulse I_{sp} = 100 sec, the amount of propellant required is $\frac{I_{TOTAL}}{I_{sp}} = \frac{5800 \text{ lb}_f\text{-sec}}{100 \frac{\text{lb}_f\text{-sec}}{\text{lb}}} = 58$ lb.

c. NH_3 density = 35.3 lb/ft^3.

d. Allowing a 5% propellant contingency, the propellant required then becomes 1.05 x 58 lb = 61 lb.

e. Allowing a 5% ullage volume, the total tank volume required becomes $\frac{61 \text{ lb}}{35.3 \text{ lb/ft}^3} \times 1.05 = 1.815 \text{ ft}^3$

f. A spherical tank with this capacity will require an inside radius of 9.1 inches.

The tank material thickness was then determined utilizing the equation $t = \frac{NPR}{2s}$, where s = 0.2% offset yield strength for annealed 304 stainless steel, P = use pressure (165 psia), R = radius, and N = safety factor. Therefore, $t = \frac{(1.5)\ (165 \text{ lb/in}^2)\ (9.1 \text{ in})}{(2)\ (30{,}000 \text{ lb/in}^2)} = 0.038$ inches.

Since the method of fabrication for the sphere was known to be either hydroforming or spinning, the tank thickness was specified to be 0.040-0.055 inches which would allow for an expected 0.015 - 0.017-inch thinout during forming when starting with 0.055-inch-thick stock. The tank procurement was based on the following specifications:

a. 18.200 ± 0.200 I.D. type 304 stainless steel sphere with a 3-inch-long 0.250 x 0.030 wall type 304 stainless steel fill and drain tube welded in each end.

b. Finished thickness of sphere to be 0.040 - 0.055 inches.

c. All welds to be helium mass spectrometer leak checked. Total leakage shall not exceed 10^{-8} std. cc/sec.

d. The completed tank shall be hydrostatically pressure tested at 250 psig three times for a total of six minutes. The hydrostatic test shall not cause permanent deformation along any circumference greater than 0.12 inches. (Note: This corresponds to deflection within the material elastic limit.)

e. After hydrostatic pressure testing, the tank shall be thoroughly flushed with reagent grade methyl alcohol, rinsed with Freon-12, and dried in a stream of nitrogen.*

f. To avoid any tendency to plug the lines or orifices in the flow path, the outlet from the tank will be equipped with an in-line filter of 10μ pore size, many times smaller than the smallest passage in the flow path.

Heat Exchanger/Vaporizer Design

The single-pass tube heat exchanger was sized utilizing a computer program previously developed at General Electric. The tubing size, i.e., inside diameter and length, is computed based on the assumption of a constant wall temperature and a gaseous heat transfer coefficient prevailing throughout the total length of the heat exchanger. These assumptions are conservative since in reality wet vapor and/or liquid ammonia will enter the heat exchanger and a heat transfer coefficient much greater than the gaseous case will prevail until the liquid is vaporized. The conservative nature of the calculations was experimentally verified in some subscale feed system tests as described in Section V-I.

The information gained from the sub-scale tests made it possible to selectively pick the computer output data considered to be most nearly optimized for the 18.2-inch propellant storage tank. This engineering estimate of the tubing size was necessary because a complete theoretical analysis of a transient heat flux heat exchanger was beyond the scope of this program. The computer output sheet from which the tube size was estimated is presented in Section V-J.

*This same method was used to clean the tank prior to buildup into the system. The maximum particle size allowed was 100 microns. The process used for this operation is described in Specification 03-0050-00-A, appearing as Appendix A. The cleaning facilities are described in Specification 03-0049-00-A and is included in this report as Appendix B.

Since this type system operates during a declining temperature environment, it is necessary to size the heat exchanger to operate satisfactorily at low temperatures (45°F or so), with the knowledge that at higher spacecraft ambient temperatures the system will be over-designed. The final size selected for the heat exchanger tubing was 125 feet long, 0.230 inches inside diameter, and a 0.010-inch-thick tube wall.

Furnace brazing was the technique chosen for joining the heat exchanger tubing with the storage sphere. As mentioned in the system description, the heat exchanger is intimately brazed onto the exterior surface of the storage sphere. The brazing was accomplished per the specification listed in Section V-K. The procurement concept under which the brazing was completed permitted the vendor to select the braze alloy, subject to GE approval. The actual brazing fabrication technique is related in Section V-L. A drawing showing the final tank/heat exchanger design is provided in Fig. 4a.

The finished storage tank with heat exchanger/vaporizer attached was painted with Cat-A-Lac flat black high thermal emissivity paint (ϵ = 0.9) to promote radiation heat reception.

Thruster Design

The thrusters for the system were specified to produce 0.315 lb_f $\pm$ 20%. The design chamber pressure selected was 22.25 psia. This pressure choice is a result of an examination of the possible ranges of regulated thruster gas supply pressure possible with this type of vaporizing system, plus the necessary pressure for good supersonic nozzle characteristics. Since the system concept utilizes a sizable pressure drop in the heat exchanger tubing to obtain a large heat transfer coefficient, the amount of pressure available at the thruster nozzle may not be much higher than 30 psia or so, depending on how low the spacecraft temperature may drop. Therefore, the pressure chosen was 22.25 psia.

Following the decision to regulate the ammonia gas pressure at the nozzles to 22.25 psia, the next step was to size the nozzles. The nozzle sizing is accomplished through the use of the already available GE(NSP) computer programs which calculate the performance of an axisymmetric supersonic nozzle with laminar boundary layer. The first step was to use the computer program with approximately 24 known sizes scaled from pre-

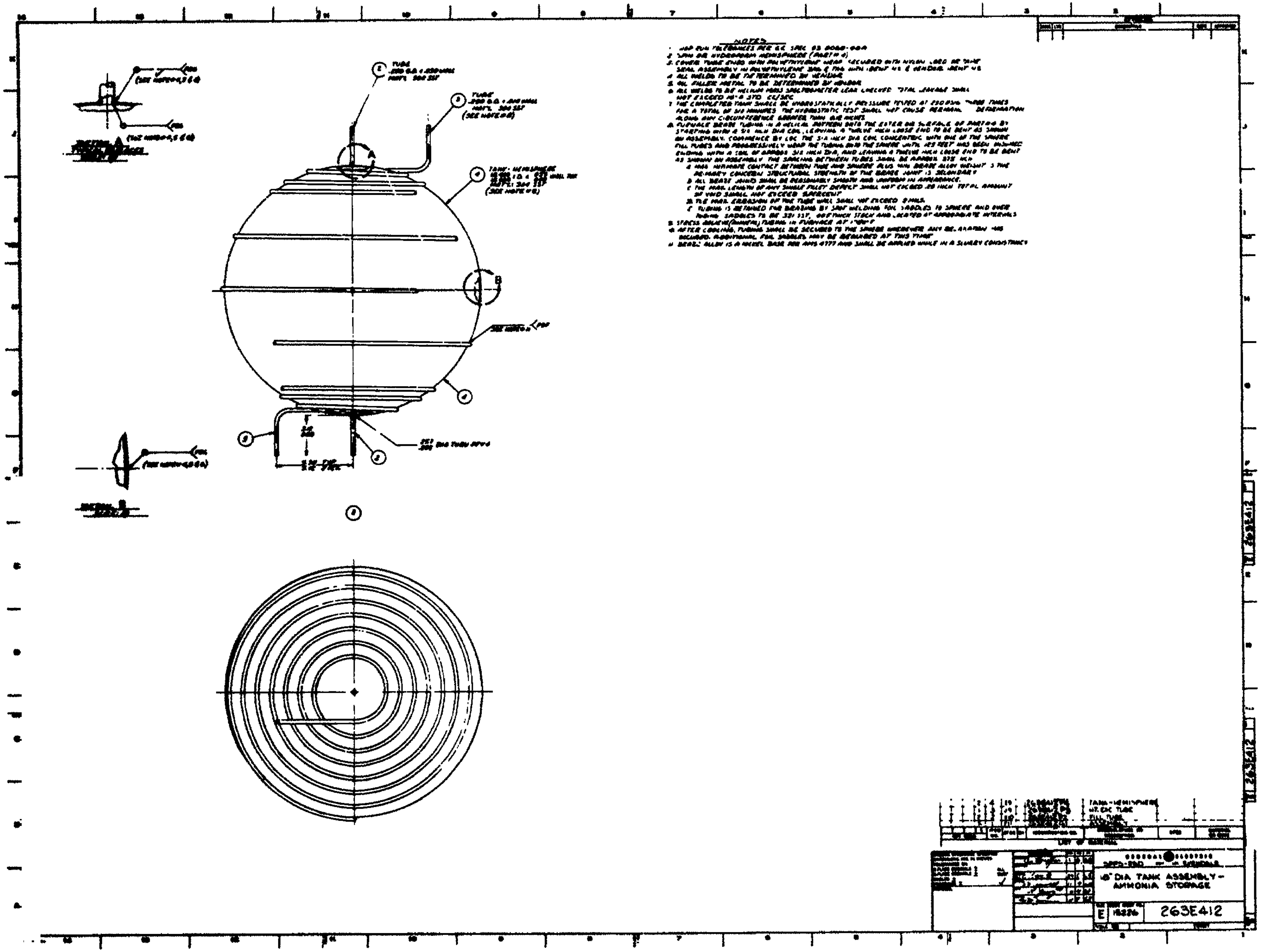


Figure 4a. Engineering Drawing of Storage Tank/Heat Exchanger. (Dwg. #263E412)

viously designed nozzles as input data. Then the output data closest to the desired nozzle characteristics were extracted and plotted. The desired nozzle size is then extracted from the graphical plot and run on the computer for confirmation of thrust and predicted I_{sp}.

The nozzle size which will produce the desired performance is depicted in the solenoid valve drawing, Figure 5. It should be noted that the nozzle is designed to fit directly onto the outlet of the solenoid. Following the receipt of the nozzles from the vendor, the precise size was obtained through precision measurements and the computer was again employed to make a predicted performance calculation for the nozzle while operating in hard vacuum. The results of this computer run are presented in the reproduced computer output sheets in Section V-M Also presented is the predicted performance of the nozzles when operating with various ambient back pressures. Those calculations were made to get an advance indication of nozzle performance with back pressure since the vacuum facility to be used for system testing will be unable to exhaust 6.3×10^{-3} lb/sec ammonia gas (two nozzles operating simultaneously) and maintain zero millimeters mercury ambient pressure.

It is noted from Section V-M that the expected degradation in nozzle performance will be within the $\pm$ 20% thrust level specified for this program. A photo of a detachable thruster nozzle is presented in Figure 6. The engineering print showing method of "O"-ring sealing and direct mounting on the solenoid valve is presented in Figure 5.

Solenoid Valve and Filter Design

There are three separate solenoid valve requirements for the laboratory system - (1) the two valves which operate in low-pressure ammonia gas (22.25 psia $\pm$ 20%), SV-3 and SV-4 (Figure 3); (2) the vapor feed valve SV-1, operating in gaseous ammonia at 70-140 psia; and (3) the liquid feed valve SV-2, operating in liquid ammonia at 70-140 psia.

In the laboratory system design one single solenoid valve size was used for all three locations for reasons of economy and simplicity.

The solenoid valve used was sized by Allen Design Incorporated, Burbank, California, to incorporate a 0.140-inch-diameter orifice flow path, which will restrict pressure losses to 1% - 7% for inlet pressures of 23-140 psia, respectively. The operating voltage is 18 V.D.C.

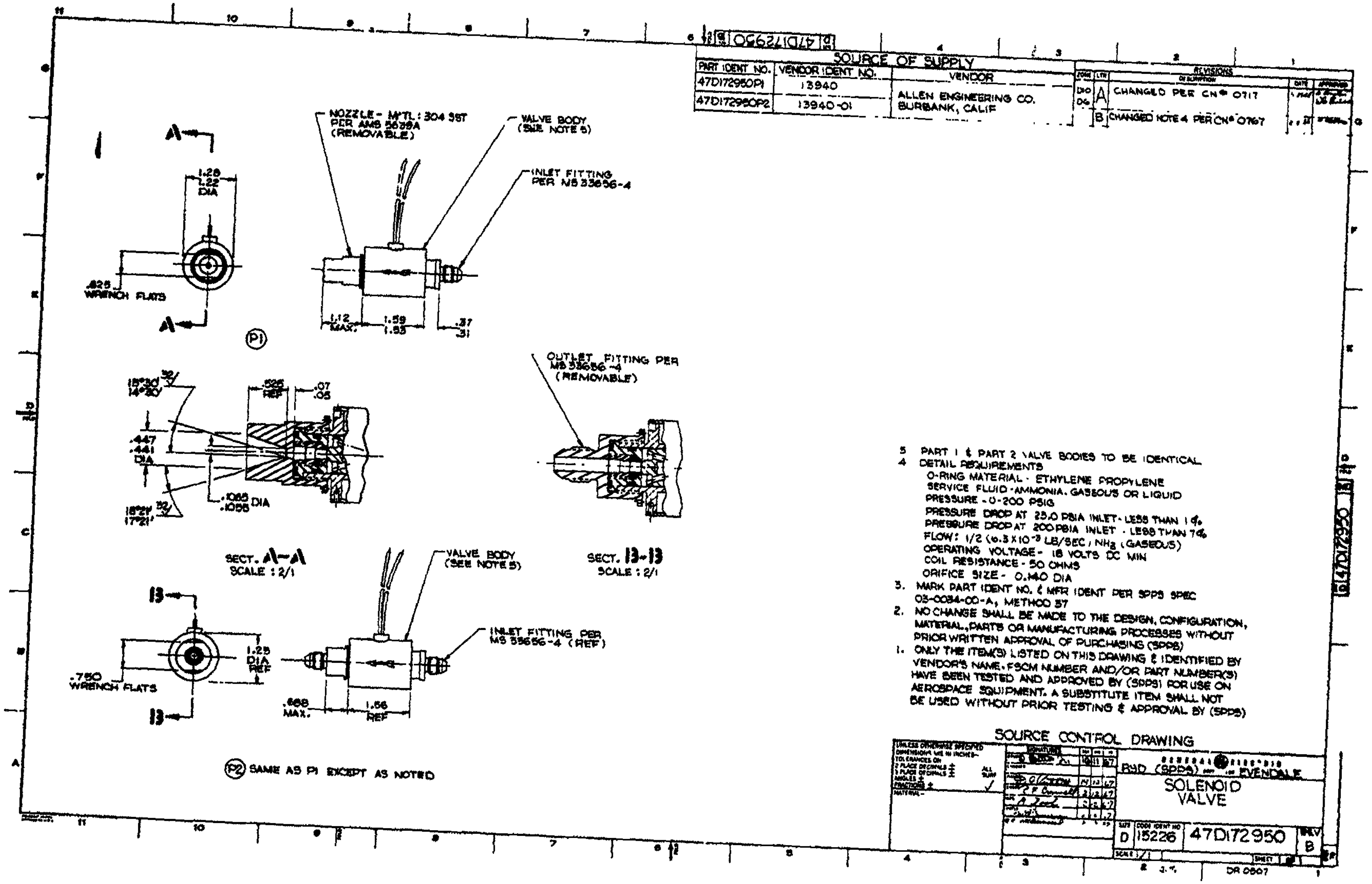


Figure 5. Solenoid Valve and Thruster Nozzle. (Dwg. #47D172950)

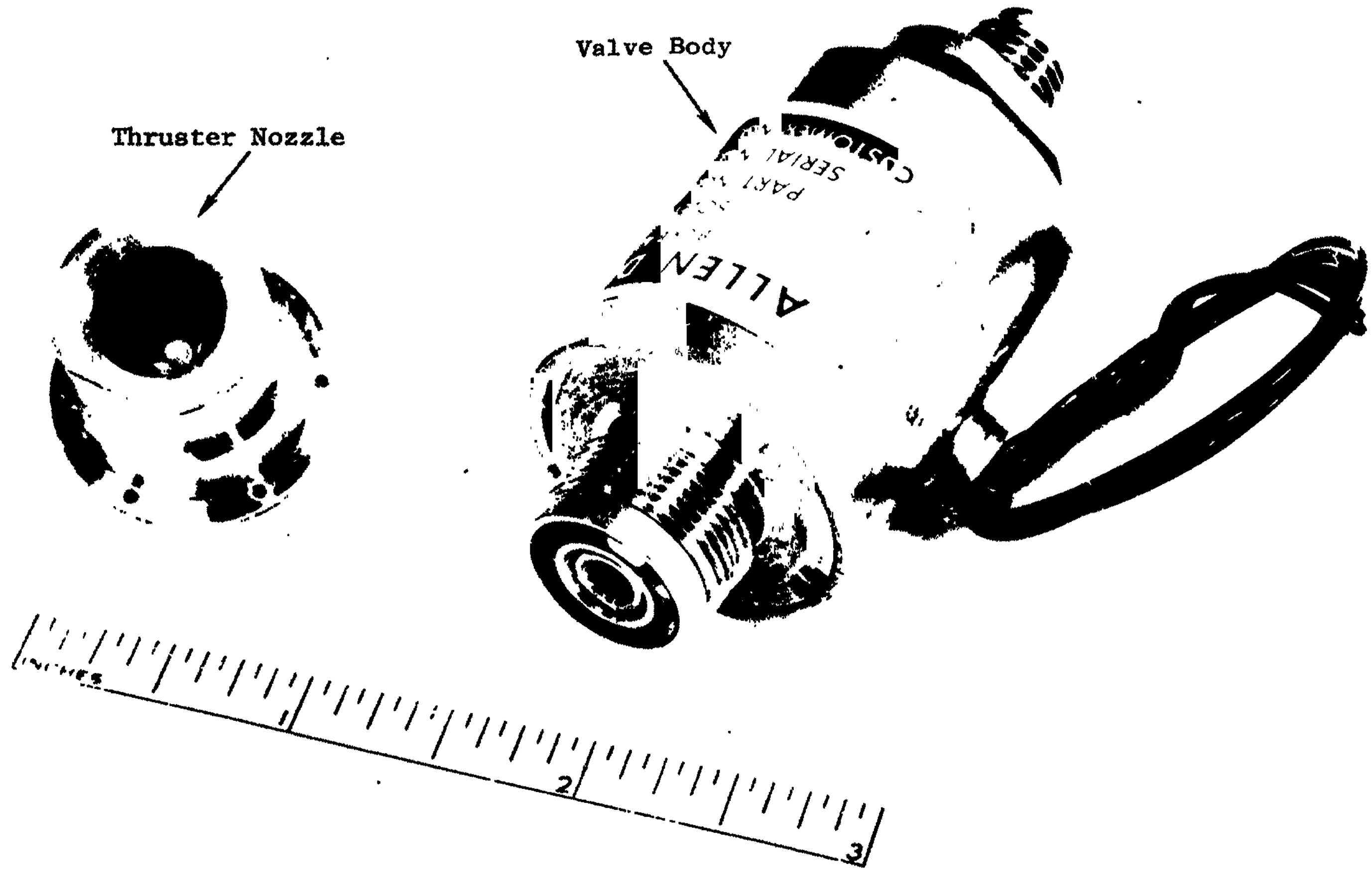


Figure 6. Solenoid Valve with Detachable Thruster Nozzle.

minimum. This solenoid valve is sized precisely for the thruster nozzle and is over-sized for both the liquid feed valve SV-2 and vapor feed valve SV-1. A descriptive photo of the solenoid valve is presented in Figure 7. The engineering drawing of the solenoid valve is presented in Figure 5.

The filter selected for protection of the solenoid valves is the 60-micron filter seal by Wester Filter Company, Incorporated, Figure 8. The seal consists of a truncated cone-shaped seal which mates with standard AN flare fittings attached to, and acting as a support for, a cylindrical filter screen. The material of construction is 304 stainless steel with Heliarc welded fabrication. The filter was to be installed at the inlet of each in-line solenoid valve, i.e., SV-1 and SV-2.

Gas Pressure Regulator Design

The gas regulator is a vendor-designed component. The operating requirements for the regulator are described in the specification presented in Section V-N. Generally, the regulator is to maintain an outlet pressure of 22.25 $\pm$ 0.25 psia output at a mass flow rate of 6.3×10^{-3} lb/sec gaseous ammonia. Regulators which would meet the specification were designed by two qualified vendors, but were not built due to budgetary limitations and a lead time which would have placed receipt beyond the program finish date. For future reference, the vendors were Sterer Engineering and Manufacturing Co., Los Angeles, California and Carelton Controls Corp., East Aurora, New York.

A discussion of the gas pressure regulation problems encountered and the final regulators used for the System Tests are described in Section V-F.

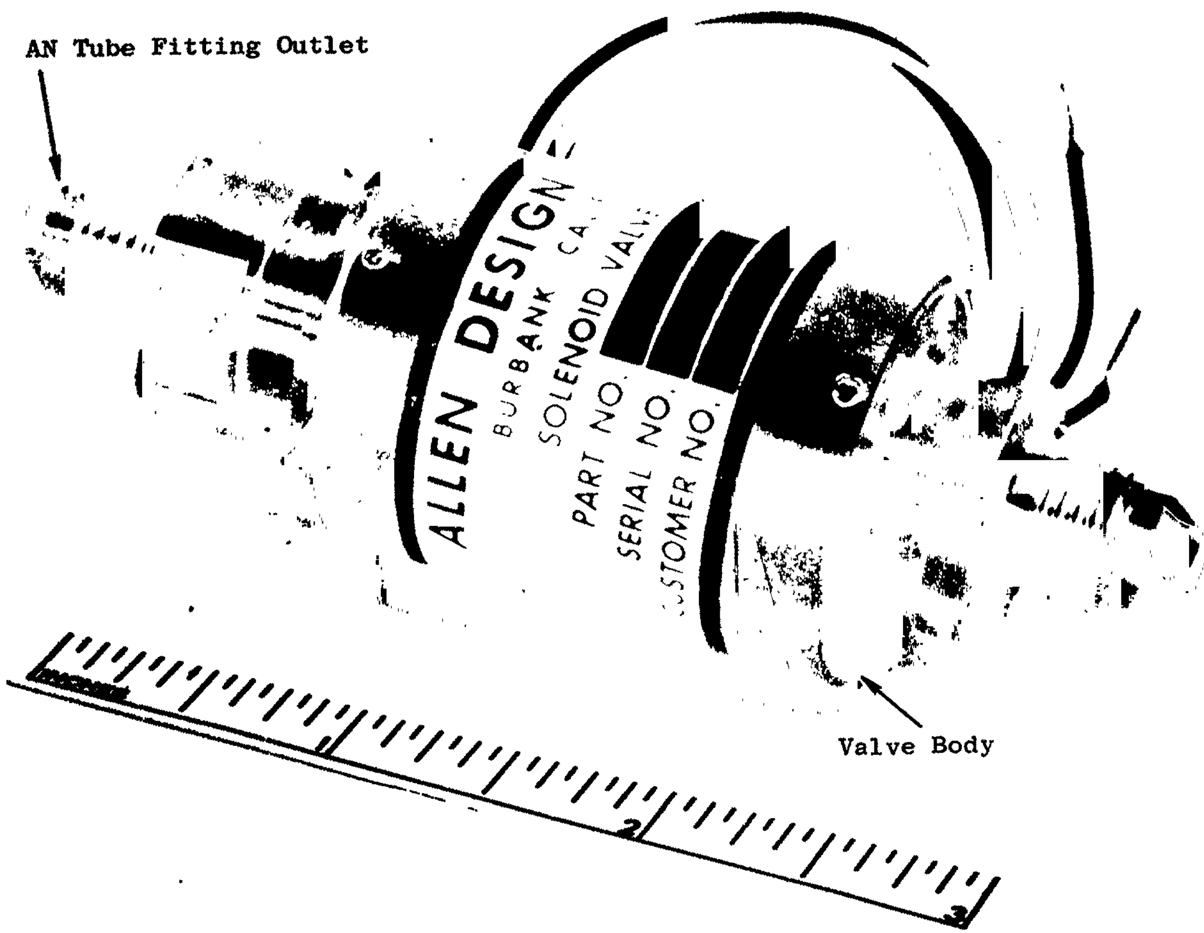


Figure 7. Inline Solenoid Valve with Tube Fitting Outlet.

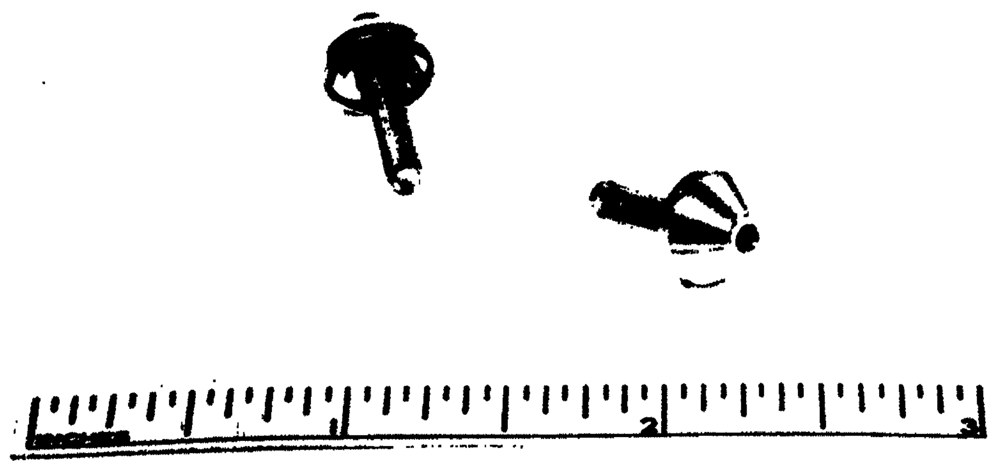


Figure 8. System Inline Filters.

Throttle Valve Design

The feed system design incorporates a throttling valve which operates in conjunction with the tubular heat exchanger. The throttle valve is located at the entrance to the heat exchanger tubing and is necessary for system operation. The reason for the throttle valve is twofold. The first is described in Section V-F, which is to provide automatic compensation for either liquid or vapor effluent from the storage tank under zero-g operation. The second reason is to accomplish proper thermodynamic throttling of the ammonia as a prerequisite for the ammonia entering the heat exchanger tubing. The throttle valve produces a pressure differential during periods of propellant flow between the storage tank and the vaporizer. The pressure differential causes a corresponding saturation tempara-ture differential to exist between the storage tank and the throttled ammonia, thus establishing a temperature potential necessary to initiate the heat transfer process from the storage tank sensible heat, to the ammonia in the heat exchanger tubing.

The type of throttling valve selected for use on the system is a spring-loaded poppet check valve. The particular model chosen is that fabricated by Republic Manufacturing Company, model number 488-4-SS-T-20, with a spring specified to obtain 25 psi throttling pressure drop. The valve is constructed of 300 series stainless steel, and was supplied with an ethylene propylene seat for long-term compatibility with ammonia liquid and vapor. This valve is shown in Fig. 9.

E. TESTING REQUIREMENTS

INTRODUCTION

The second major task of this program was to conduct a testing program on the laboratory prototype system with a testing philosophy directed

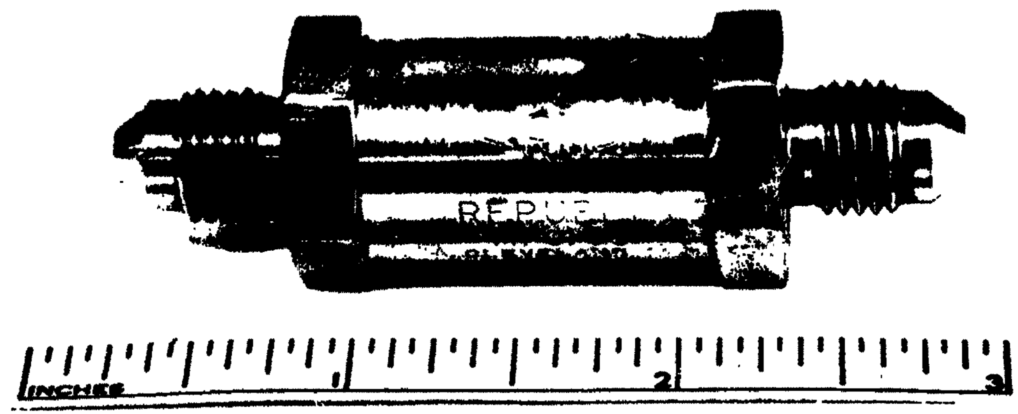


Figure 9. Throttle Valve.

toward (1) obtaining basic information which would enlarge the practical body of knowledge of the system, and (2) demonstrating successful gas generation operation of the feed system concept.

DATA REQUIREMENTS

As an aid to understanding the test data point terminology, refer to Figure 10, System Instrumentation. The test plan and data requirements are divided into two sections as follow:

System Check and Calibration Test

1. Test Condition
   a. Vacuum - ambient
   b. Room temperature
2. Purpose
   a. Determine system operability
   b. Determine system instrumentation calibration
   c. Operational checkout of test equipment
   d. Determine leakage
3. Mode of Operation
   a. Liquid feed mode
   b. Vapor feed mode
   c. Pulse - at nominal thrust to gain familiarity with system characteristics.
   d. Continuous thrusting - total of 1/2 hour operation or until regulator input pressure (P_3) drops below 2 times output pressure (P_4).
4. Measured Data
   a. Thruster thrust
   b. Storage tank temperature (T_6)
   c. Storage tank pressure (P_1)
   d. Nozzle inlet pressure (P_4)
   e. Nozzle temperature (T_5)
   f. Line pressures (P_2, P_3, P_4)
   g. Heat exchanger wall temperatures at 10-foot intervals (TC-11 through TC-20)
   h. Throttle valve inlet and outlet pressures ard temperatures (P_1T_1 and P_2, T_2).

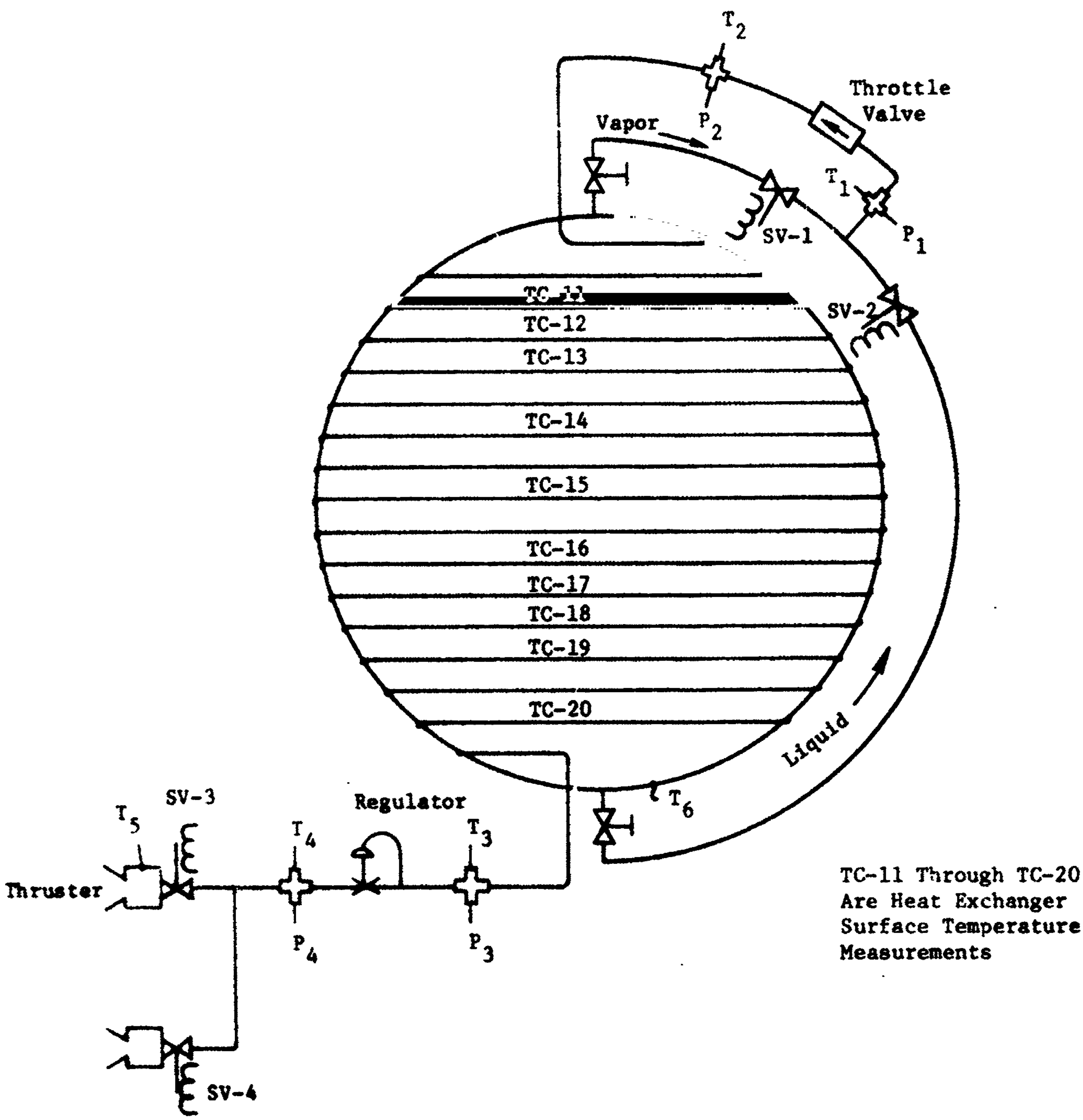


Figure 10. System Instrumentation.

i. System thermal decay

5. Calculated Data

a. Gas flow rate

System Performance Test

1. Test Conditions

a. Vacuum - ambient

b. Storage tank temperature - from room temperature down to approximately 45°F.

2. Purpose

a. Demonstrate capability of system to operate with either liquid or vapor feed into the heat exchanger, and produce superheated gas at the heat exchanger outlet.

b. Determine system parameters such as pressures, temperatures, and specific impulse.

3. Mode of Operation

a. Liquid feed

b. Vapor feed

c. Alternating liquid-vapor feed

d. Two nozzles simultaneously

e. Variable storage tank propellant levels (100%, 75%, 50%, 25%)

4. Measured Data

a. Thruster thrust

b. Tank temperature (T_6)

c. Tank pressure (P_1)

d. Nozzle inlet pressure (P_4)

e. Nozzle temperature (T_5)

f. Line pressure (P_1, P_2, P_3, P_4)

g. Throttle valve inlet and outlet pressures and temperatures (P_1, T_1 and P_2, T_2).

h. Electrical power requirements (SV-1, SV-2, SV-3, SV-4)

5. Calculated Data

a. Specific impulse

b. Heat transfer rates

c. Gas flow rates

TEST FACILITIES

The facility requirements for conducting the system test program are itemized below:

1. Vacuum Chamber - to provide a vacuum environment for proper operation of both the feed system and thrusters. The vacuum chamber will simulate a constant temperature spacecraft radiation heat source for the feed system. The thrusters require a vacuum environment greater than 20,000 microns for satisfactory performance; refer to Appendix E for elaboration.

The vacuum facility at GE(NSP) Evendale, Ohio, Figure 11, incorporates a Stokes Model 1721 which can achieve this low pressure with a gaseous ammonia flow rate of 6.3×10^{-3} lb/sec into the chamber.

The vacuum system will also be needed for filling the propellant tank. See Section V-O for a description of the filling technique.

2. Propellant storage tank support structure - the propellant storage tank had to be sturdily mounted inside the vacuum chamber, yet permit easy removal for filling and weighing. An aluminum cage structure with a nylon storage tank support sling was assembled, Figures 12 and 13, to fulfill this requirement.

3. Thrust Rig - The thrust rig is used to measure the thruster output. The thrust rig is a sensitive instrument, suspended inside the vacuum chamber, which will allow measurement of the output of one thruster. A pictorial view of the thrust rig is shown in Figure 14. (The linear displacement force transducer was not installed in its mount at the time the photo was taken.) The thrust rig utilizes a segment of the propellant flow tubing for thrust rig suspension. The spring hysteresis of the tubing is accounted for in the calibration of the displacement transducer.

INSTRUMENTATION

The test instrumentation used for measurement and control of the system operation is itemized as follows:

a. DC power supply
b. Eight channel Sanborn Model 150 strip chart recorder
c. Solenoid valve control switches
d. Honeywell 24 point temperature recorder
e. Hewlet Packard Model ?TA 100-1 (0-100 gram) linear displacement transducer
f. Type K (Chromel-Alumel) thermocouples

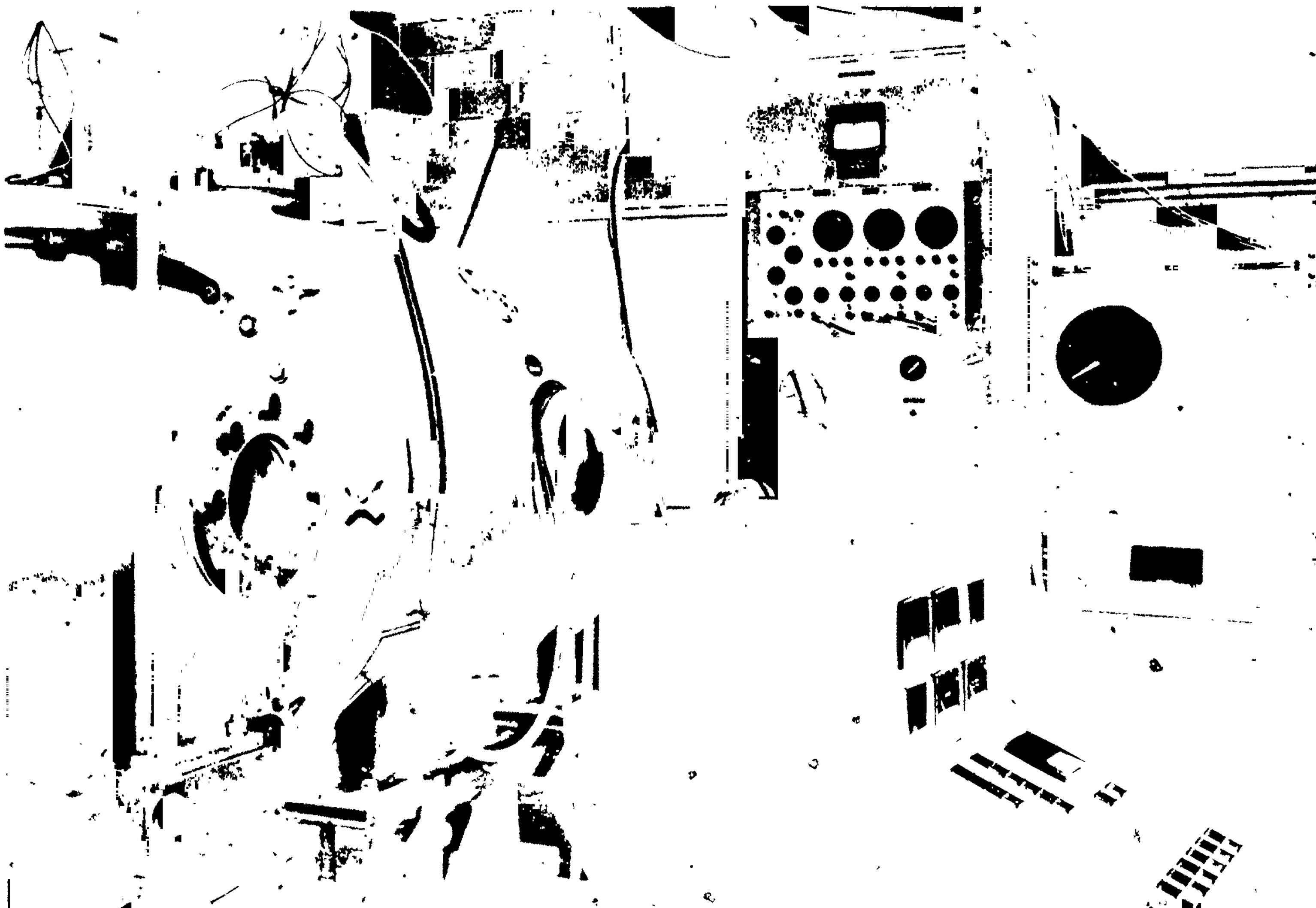


Figure 11. 2½ x 5 ft. Vacuum Chamber

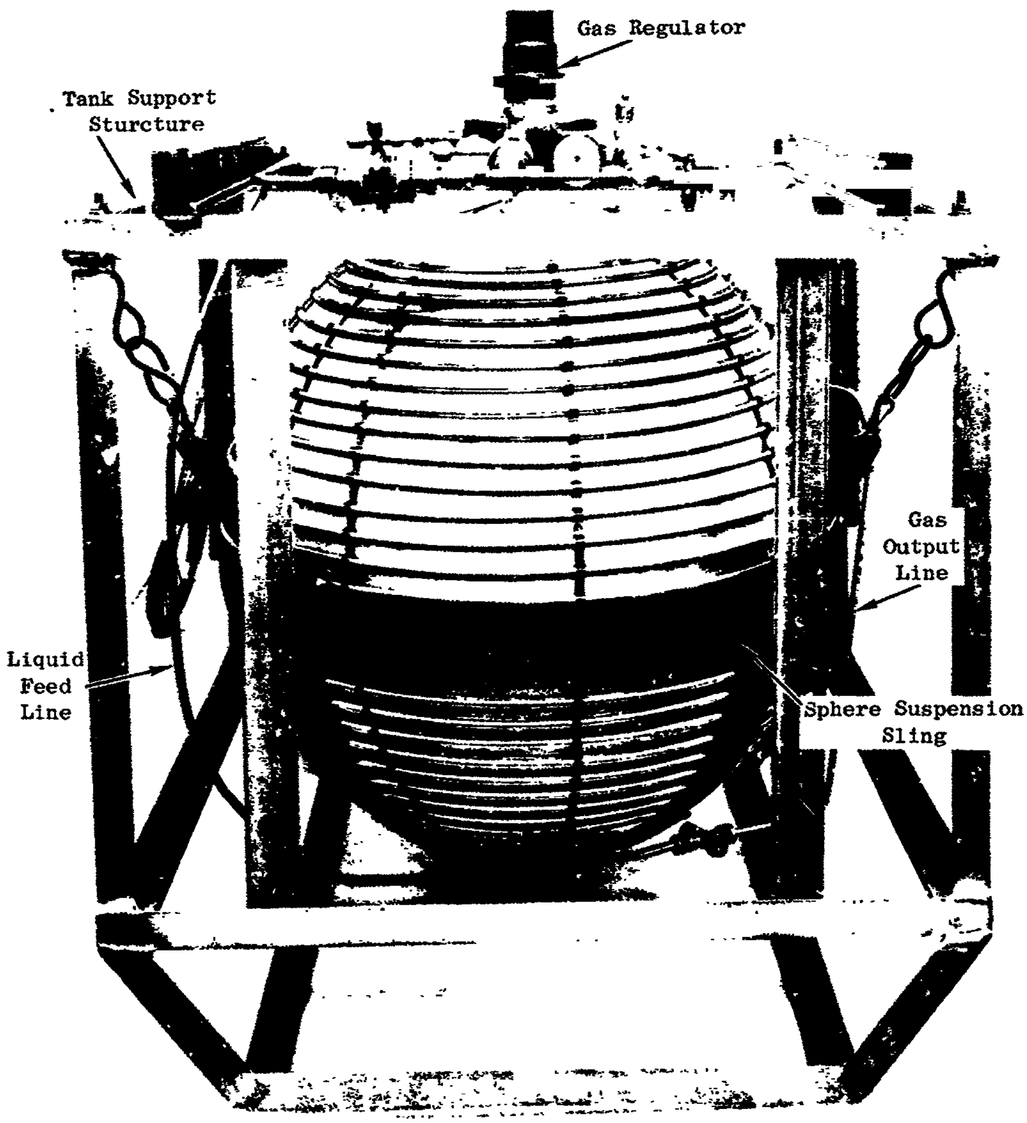


Figure 12. Feed System Components Mounted in Support Structure (End View).

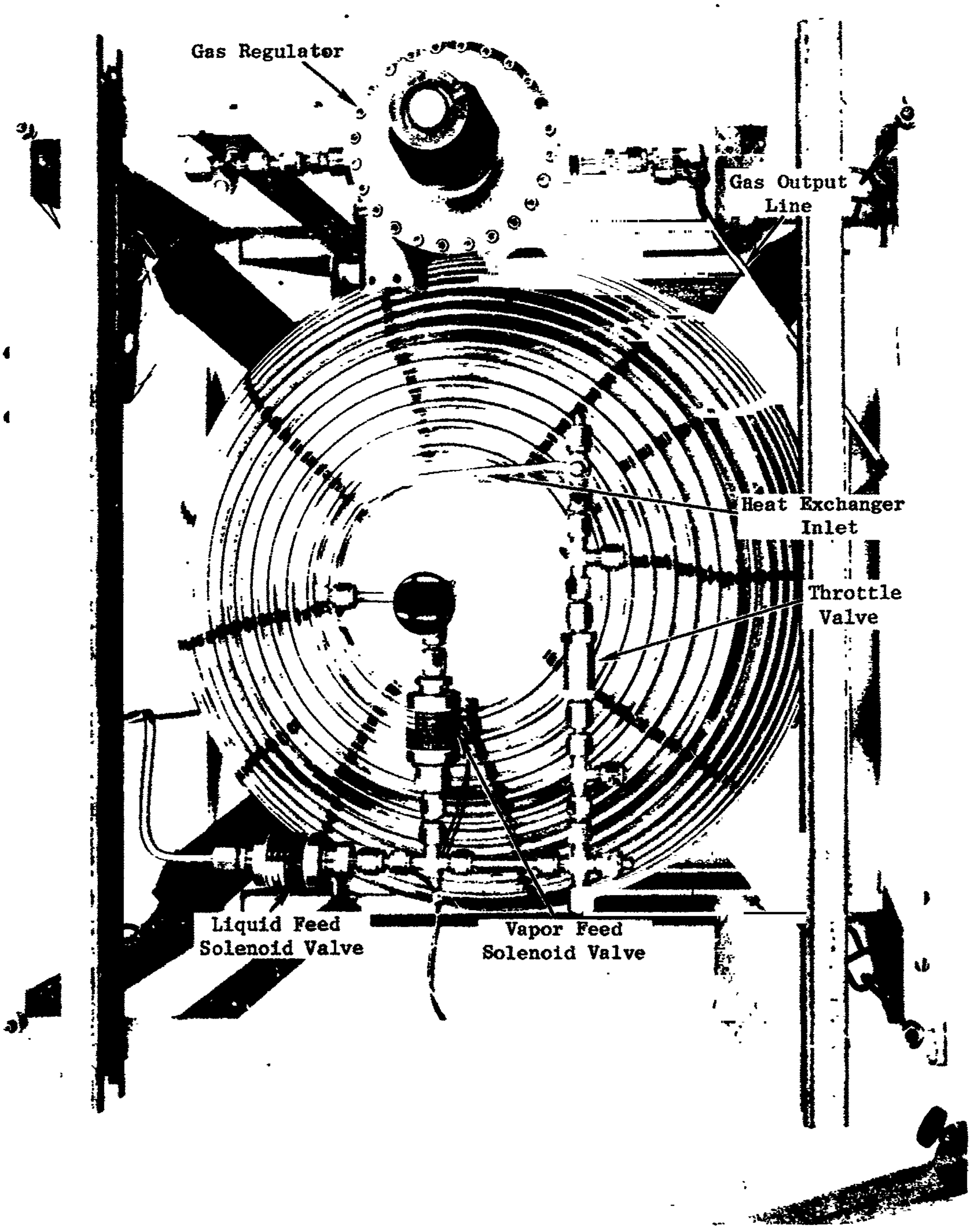


Figure 13. Feed System Components Mounted in Support Structure (Top View).

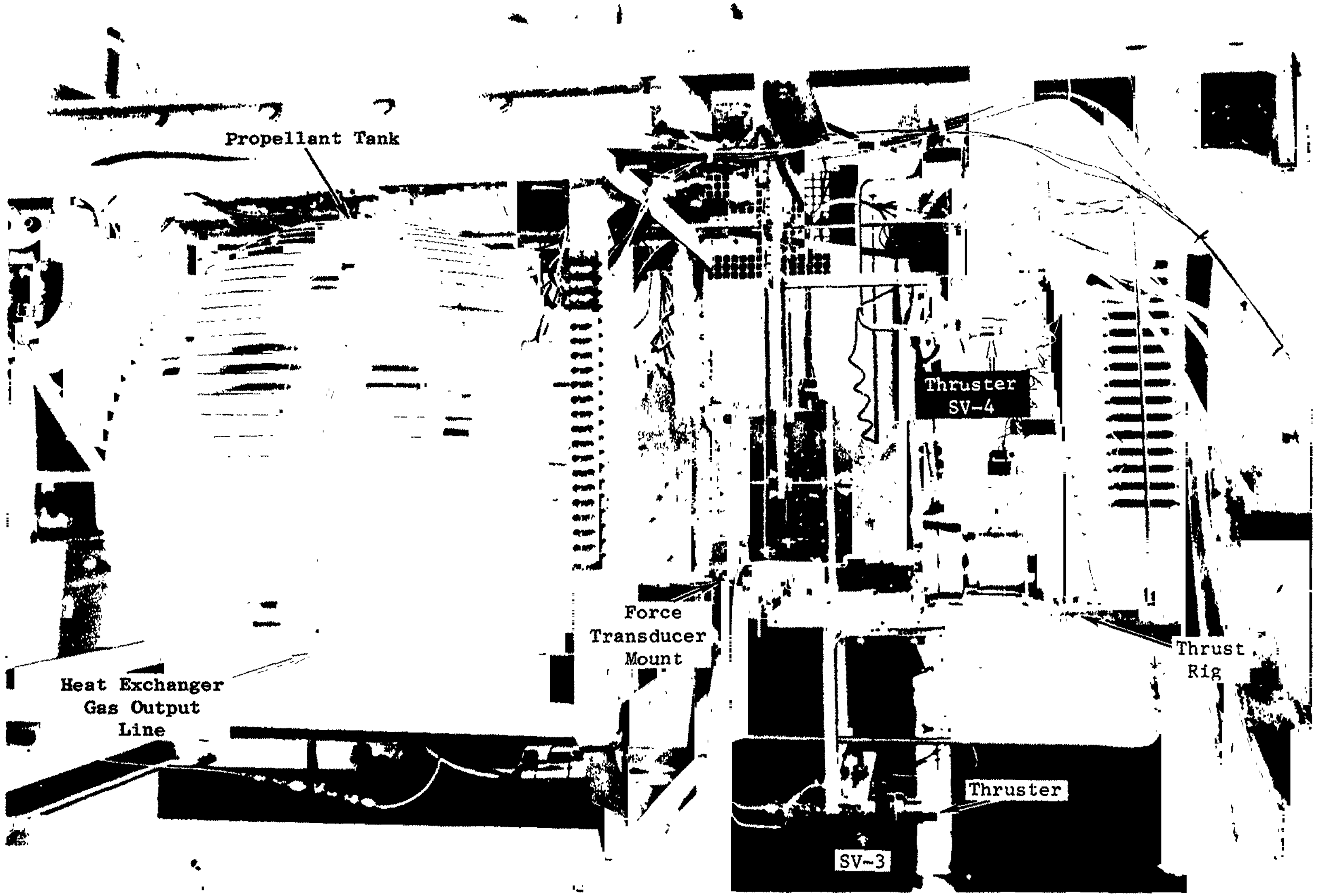


Figure 14. Side View of System.

g. Teledyne Type 217-SA, 227, and 217 pressure transducers

h. Statham pressure transducer

The thruster thrust was sensed by the Hewlet Packard linear displacement transducer, which was statically mounted to the facility so that the movable stylus touched the thrust rig table. This thrust measurement system was calibrated so that the thruster force output could be recorded directly in millipounds on the Sanborn strip chart recorder.

The thruster chamber pressure (P_4) was measured with the Teledyne Type 217 (0-100 psia) transducer, the throttle valve outlet pressure (P_2) with the Statham (0-200 psia) transducer, and the throttle valve inlet pressure (P_1) with the Teledyne Type 217-SA (0-200 psia) transducer. The pressure transducers were all calibrated in vacuum (60 microns) against a known pressure of static nitrogen gas read on a Wallace & Tiernan Model FA 233 reference gage. The pressure data from all transducers were recorded on the Sanborn strip chart recorder.

All temperature measurements were made with Type K (chromel-alumel) thermocouples. The propellant temperature measurements at T_2, T_3, and T_4 utilized 1/16-inch-diameter, stainless-steel-sheathed, thermocouples projecting into the flow path. These thermocouple outputs were recorded on the Sanborn instrument. One other temperature (T_5), sensed by a spot welded thermocouple on the thruster nozzle, was recorded on the Sanborn instrument.

The other system temperatures, T_1, T_6, and TC-11 through TC-20 were recorded on the Honeywell multipoint recorder. Thermocouples TC-11 through TC-20 were attached to the surface of the heat exchanger tubes with Ecco Bond 285 epoxy cement.

The most important data sought from the system testing were recorded on the Sanborn strip chart recorder. This data revealed the state of the ammonia propellant at the critical points in the system. These data points allow continuous determination of whether the propellant is superheated or a wet vapor.

The data obtained from the heat exchanger thermocouples were used to make a rough determination of the position of the liquid boiling region in the heat exchanger. This was not intended to give precise quantitative information but rather a general indication. As it turned out, the temperatures varied too rapidly for the multipoint recorder to always record a meaningful trend.

A general overview photo of the instrumentation, controls, and recorders is presented in Figure 15. Figure 16 shows a top view of the system mounted in the vacuum chamber support structure.

F. SYSTEM TEST RESULTS

TEST PROCEDURE

The testing phase of the program was planned to obtain basic information on the system operating characteristics under various modes of operation. The different modes are outlined in Section E, Data Requirements. Briefly stated, the test procedure consisted of the following sequence:

1. 100% full tank

    First storage tank temperature stratum - room ambient

    Long Liquid Feed Pulse - 20 sec nominal

    Long Vapor Feed Pulse - 20 sec nominal

    Long Alternating Liquid - Vapor Feed Pulse - 20 sec nominal

        Total length switch SV-1 & SV-2 from liquid to vapor each 5 sec

        Short Liquid Feed Pulses - 5 sec duration nominal

        Short Vapor Feed Pulses - 5 sec duration nominal

    Second Storage Tank - Temperature Stratum -

        Repeat same test sequence as above

    Third Storage Tank Temperature Stratum

        Repeat same sequence as above

2. 75% full tank

    Same procedure as No. 1 above

3. 50% full tank

    Same procedure as No. 1 above

4. 25% full tank

    Same procedure as No. 1 above

The test procedure was designed to take advantage of the natural thermal decay characteristic of the system to establish the second and third temperature strata; recall that the storage tank temperature declines during pulsing due to the extraction of liquid ammonia sensible heat. After the first series of tests were completed for each fill level, the storage tank would be at the second temperature stratum, whereupon the second series of tests would begin. From a practical standpoint,

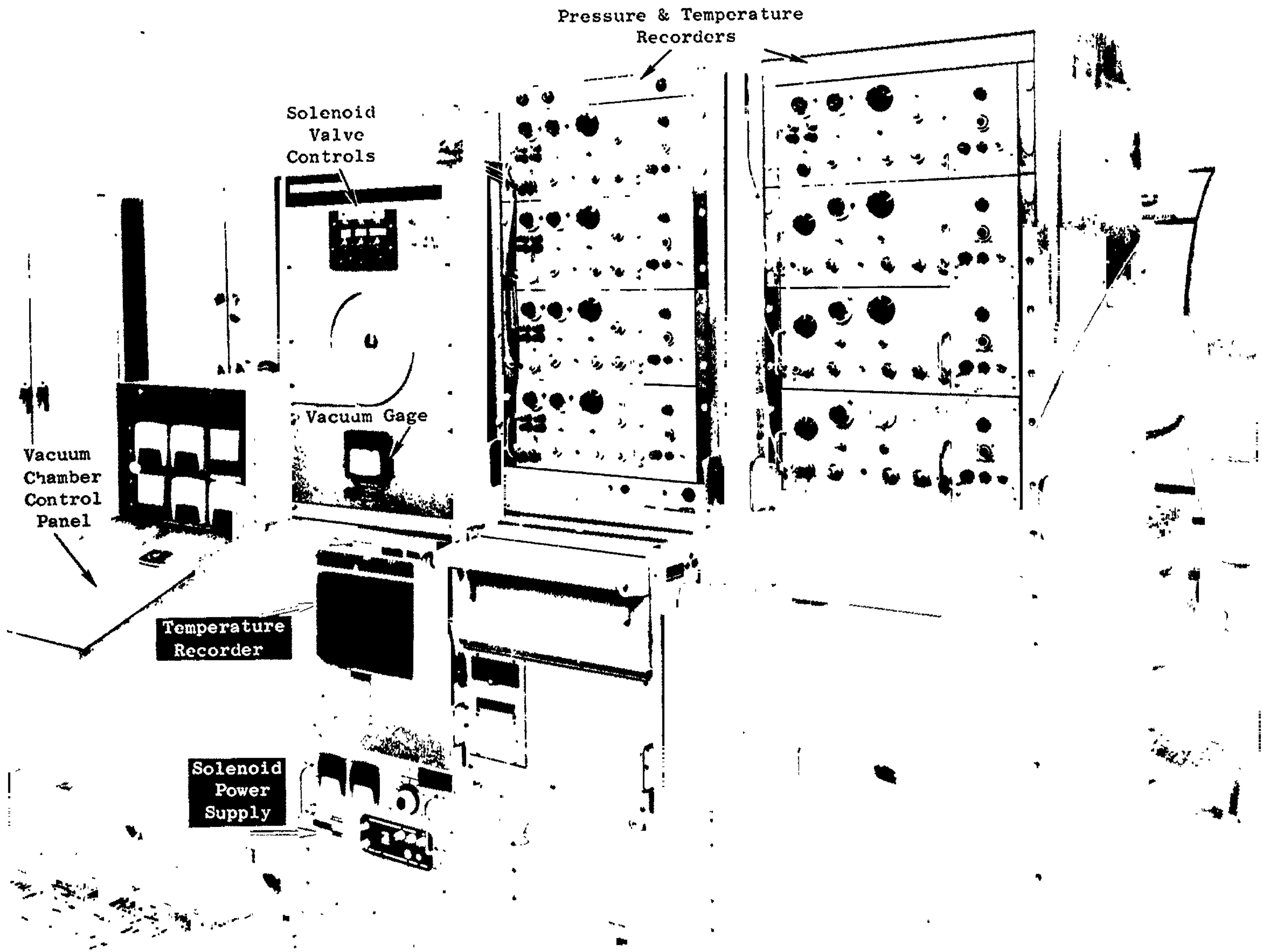


Figure 15. System Instrumentation Recorders.

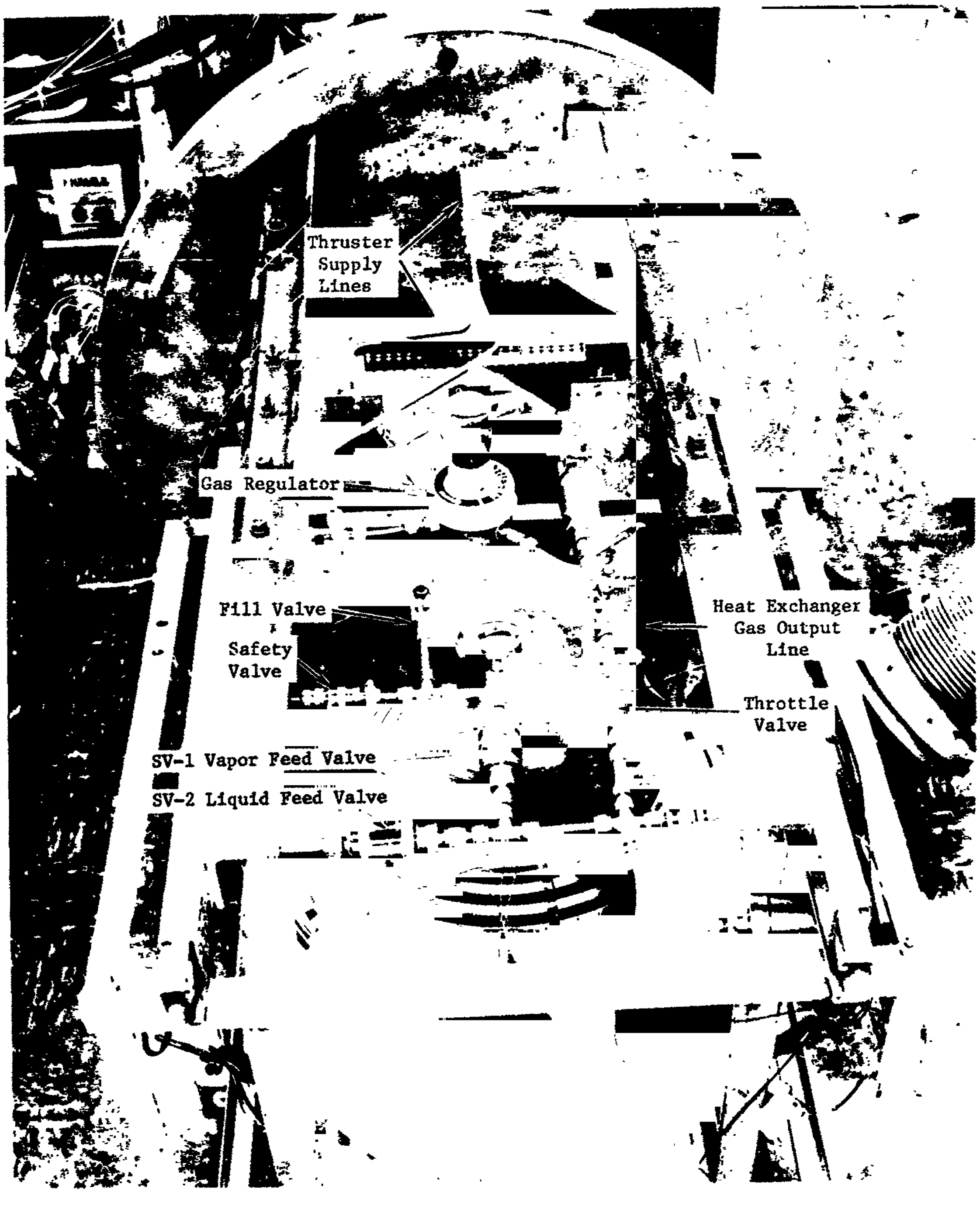


Figure 16. Top View of System.

the fill level would be unchanged (changed only by the total mass lost during the pulsing which is small in relation to the total amount of liquid in the storage tank). After the second series of tests were finished the same tests would immediately be conducted again at the third temperature stratum. After the third temperature stratum data were obtained, the test was finished for that particular fill level. The storage tank was then intentionally exhausted of sufficient propellant to diminish the contents to the next desired fill level, and then allowed to heat up to room ambient in preparation for the start of the next fill level test.

DISCUSSION OF TEST RESULTS

System Check and Calibration Check

Prior to the start of the System Performance Tests, a preliminary system check and calibration test was run. It was discovered that the ammonia gas regulator, a Matheson Co. No. 26252-30 industrial type, lacked the capacity to handle the 6.3×10^{-3} lb/sec mass flow rate and still keep the output pressure regulated. In an attempt to solve this problem, two of the Matheson regulators were joined in parallel. Unfortunately this arrangement, too, could not handle the required mass flow rate and still give a smoothly regulated 22 psia output. Under the tight schedule circumstances, the two regulators were adjusted to give the best performance in order to continue with the program testing. The most notable effects the regulator problem had on the system performance are the following:

a. Nozzle pressure P_4 was not maintained at a constant 22 psia.

b. At low regulator inlet pressures (when the storage tank temperature is approximately 50,F) the regulator served only as a line restriction and allowed P_4 to drop below design pressure.

With this exception, the preliminary system check was quite successful. The system operated within design expectations, producing superheated ammonia gas at the outlet of the heat exchanger. Operation of the throttle valve was smooth. Minor plumbing leaks were plugged through the use of an epoxy cement in the interest of completing the testing rapidly. The cement was easily removed for disassembly and component inspection. In a flight version only welded joints and/or elastomer O-ring seals would be employed, and this problem would not exist.

Following the initial system checks, the flow rate of the thruster nozzles were calibrated against upstream pressure. The technique of calibration was to allow flow for a timed period at constant pressure, with the weight of the storage tank recorded before and after the test. A calibration curve relating nozzle chamber pressure and flow rate is given in Section V-P.

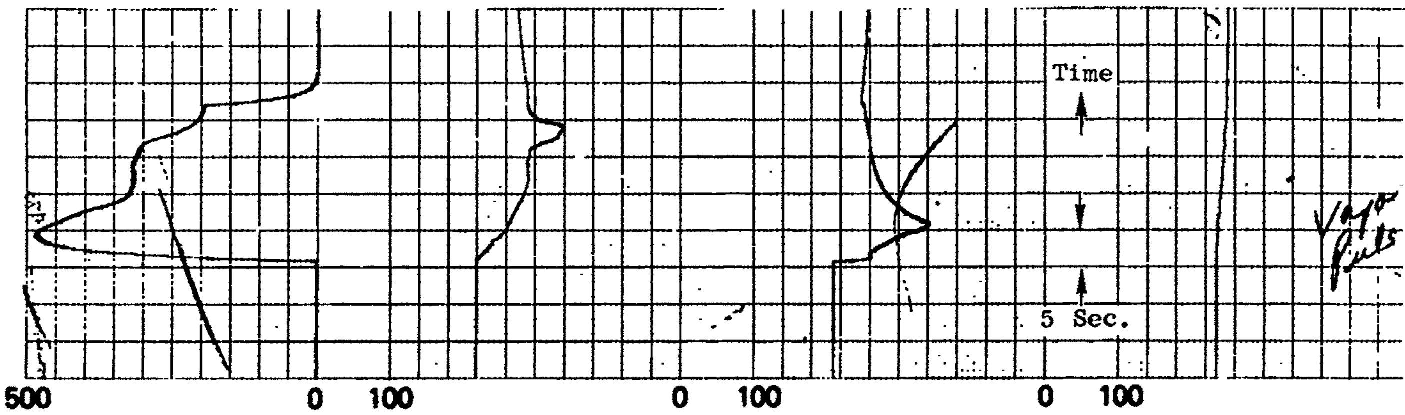
<u>System Performance Tests</u>

In the discussion of the performance test data, two main methods of data presentation are made. The first method is the presentation of reproductions of actual data traces from the Sanborn strip chart recorder. The second method is the presentation of a Mollier chart upon which is constructed an actual thermodynamic cycle which the propellant undergoes. This is done for both a liquid and a vapor pulse.

The first data were obtained with the propellant tank full, i.e., tank loaded with 60 pounds of liquid ammonia, but leaving an ullage volume in the tank [illegible] 5% of the total volumetric capacity of the tank. The data are presented in Figures 17-A through 17-F. The location of test data points can be determined by reference to Figure 10.

Figure 17-A shows the manner in which the system parameters varied during the room ambient temperature stratum (69-71°F) test for both a liquid and vapor feed pulse. The two types of pulses are shown on the same figure for comparative purposes, to point out the fundamental differences between the way the system parameters vary in reaction to whether liquid or vapor is drawn from the storage tank. First, the variations in the thruster nozzle pressure for both type pulses are noted. These are due to the gas regulator flow rate limitations noted previously. The thruster force variation is due primarily to the fluctuations in P_4. However, some of the decline noted during the pulses is due to the rising vacuum chamber back pressure reducing the effective thrust.

The characteristic of operation of the liquid feed pulse will be discussed first, followed by the vapor feed pulse discussion and some comparative comments.



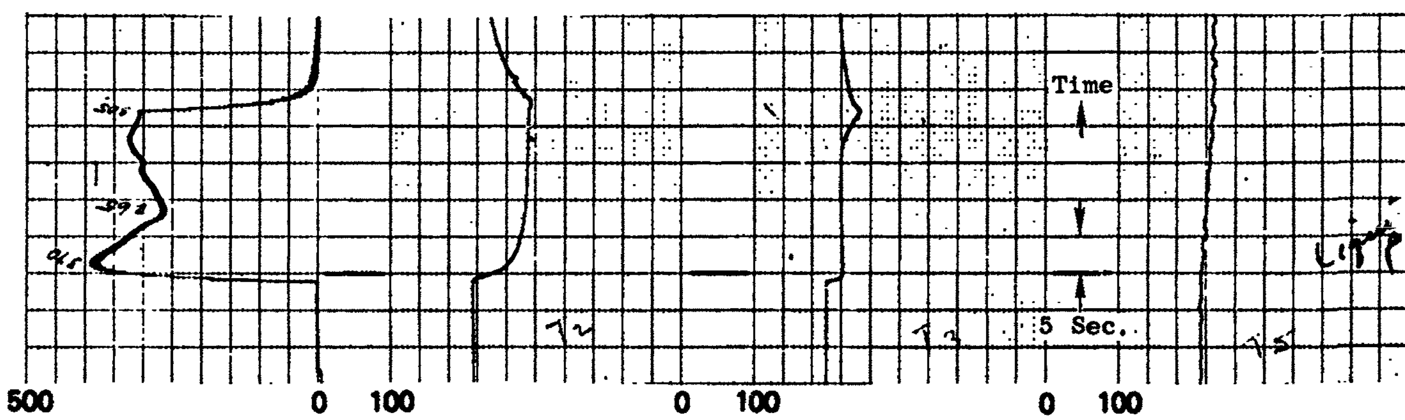
Thruster Force
lb x 10^{-3}

T_2 - Temperature at Output of Throttle Valve - ^oF

T_3 - Temperature at Heat Exchanger Output - ^oF

T_5 - Thruster Body Temperature - ^oF

Vapor Feed Pulse Data



Thruster Force
lb x 10^{-3}

T_2 - Temperature at Output of Throttle Valve - ^oF

T_3 - Temperature at Heat Exchanger Output - ^oF

T_5 - Thruster Body Temperature - ^oF

Liquid Feed Pulse Data

Figu

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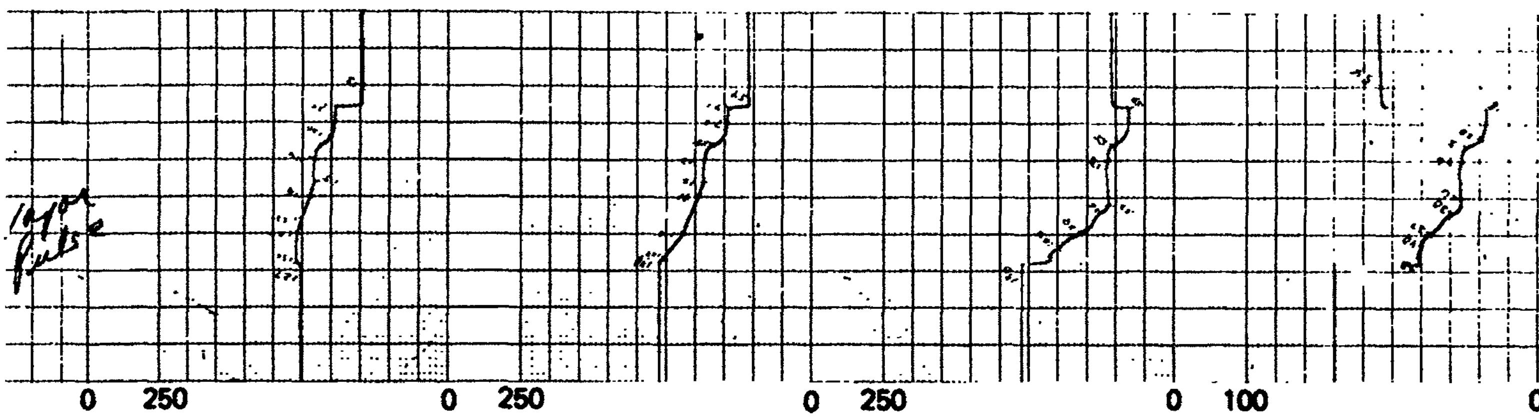
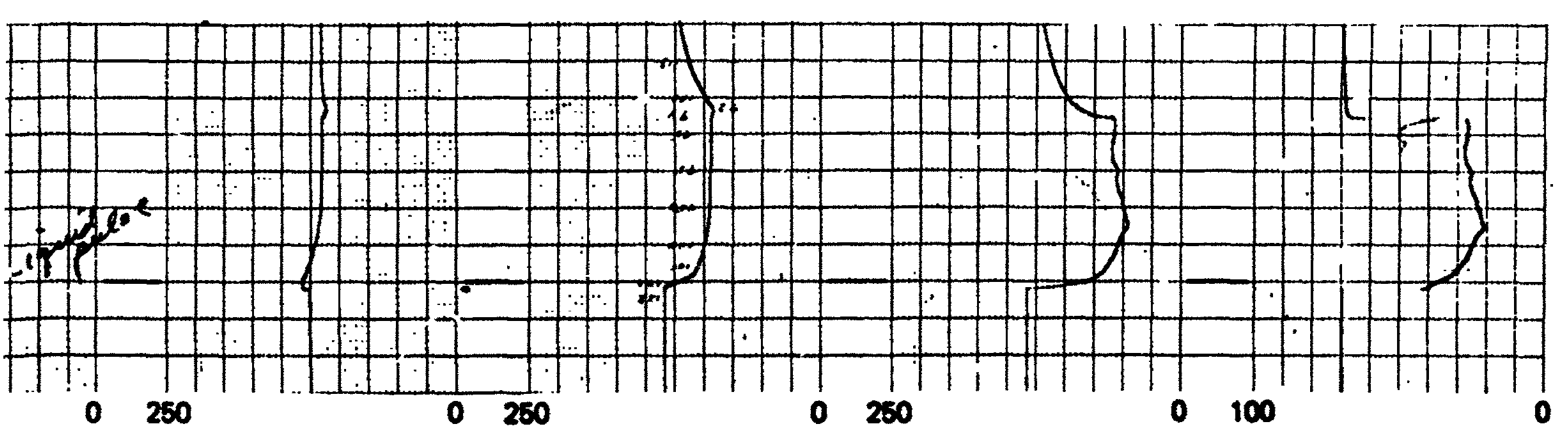


Propellant Fill Level 100%
Vacuum Tank Wall Temperature 75°F
Storage Tank Temperature 69°F



ta
Propellant Fill Level 100%
Vacuum Tank Wall Temperature 75°F
Storage Tank Temperature 71°F

Figure 17-A.

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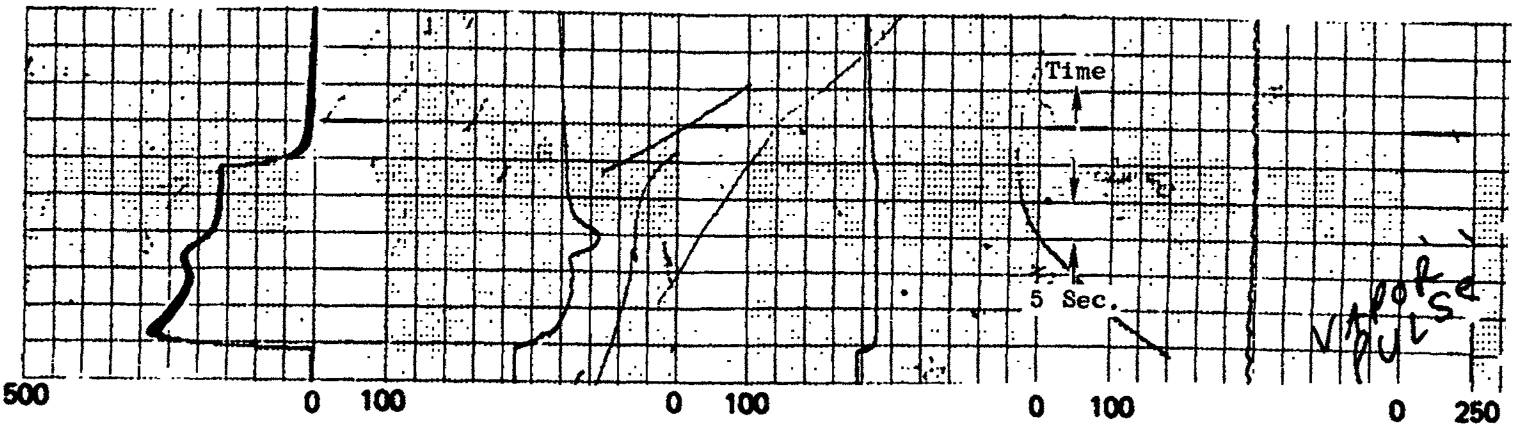


Thruster Force
lb x 10^{-3}

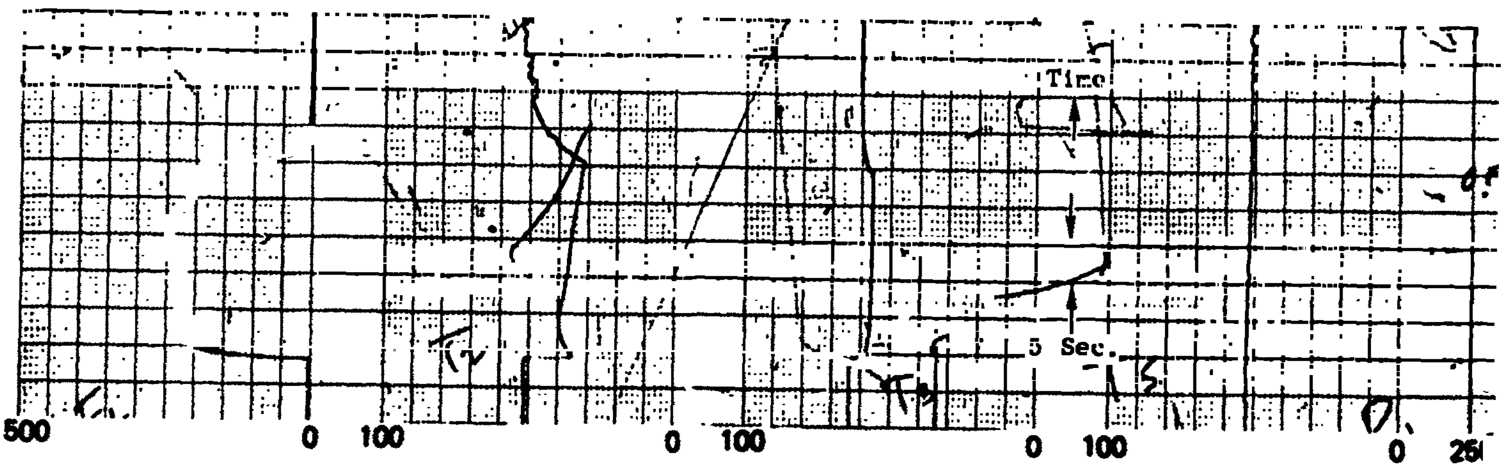
T_2 - Temperature at Output of Throttle Valve - ^oF

T_3 - Temperature at Heat Exchanger Output - ^oF

T_5 - Thruster Body Temperature - ^oF

F
I

Vapor Feed Pulse Data { Propella
Vacuum T
Storage



Thruster Force
lb x 10^{-3}

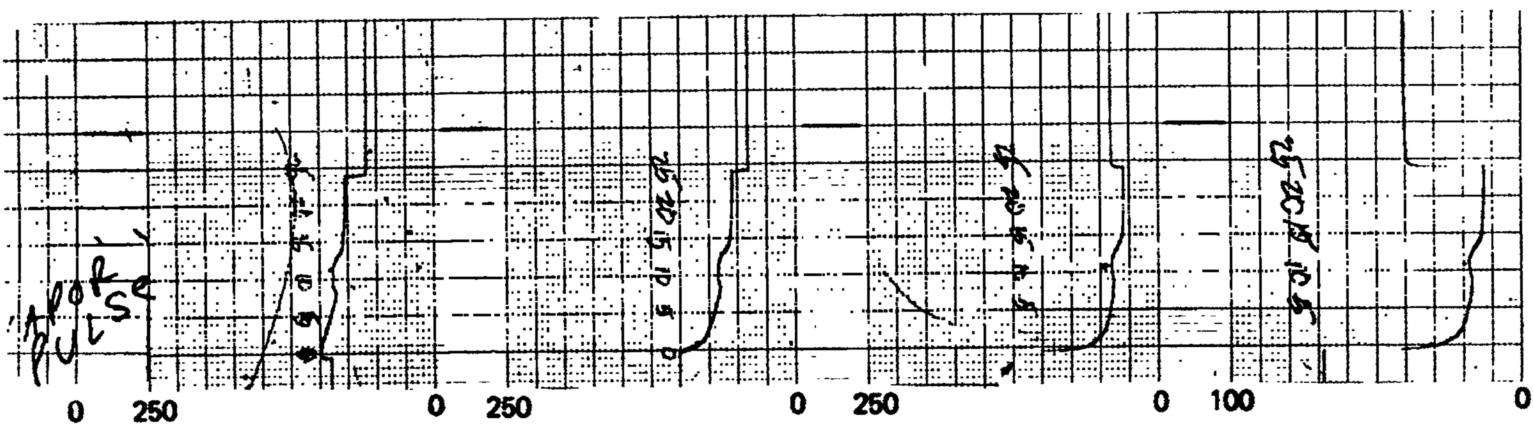
T_2 - Temperature at Output of Throttle Valve - ^oF

T_3 - Temperature at Heat Exchanger Output - ^oF

T_5 - Thruster Body Temperature - ^oF

Liquid Feed Pulse Data { Propel
Vacuum
Storage

Figure 17-



Body °F

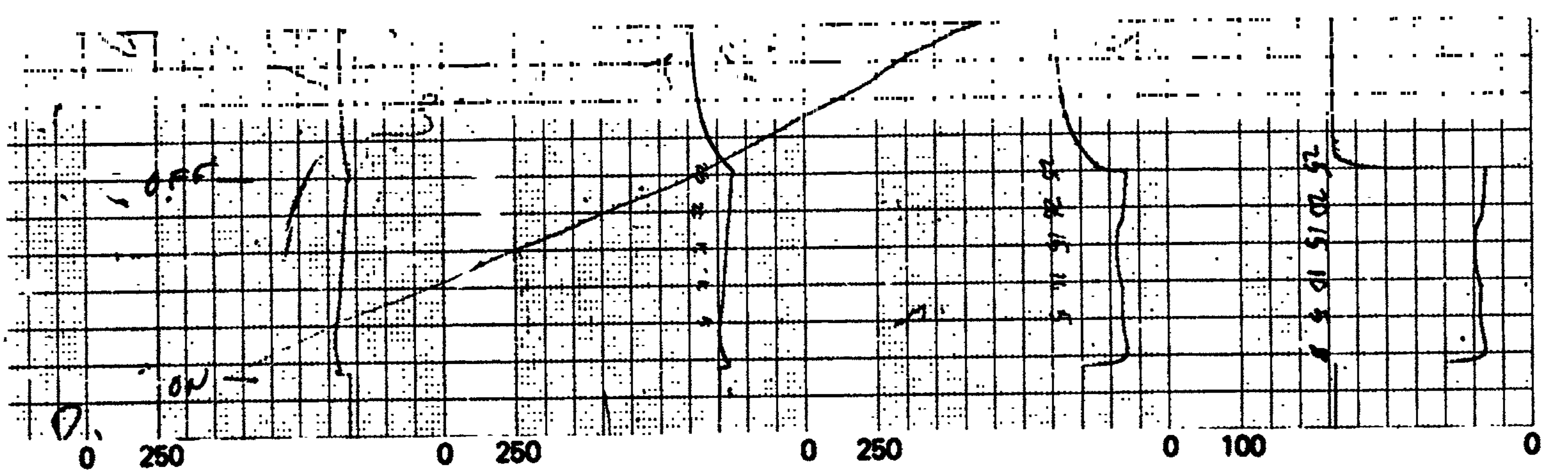
P_1 - Pressure at Inlet to Throttle Valve - Psia

P_2 - Pressure at Outlet of Throttle Valve - Psia

P_3 - Pressure at Outlet of Heat Exchanger - Psia

P_4 - Thruster Nozzle Pressure - Psia

Propellant Fill Level 100%
Vacuum Tank Wall Temperature 75°F
Storage Tank Temperature 56°F



Body - °F

P_1 - Pressure at Inlet to Throttle Valve - Psia

P_2 - Pressure at Outlet of Throttle Valve - Psia

P_3 - Pressure at Outlet of Heat Exchanger - Psia

P_4 - Thruster Nozzle Pressure - Psia

Propellant Fill Level 100%
Vacuum Tank Wall Temperature 75°F
Storage Tank Temperature 57°F

Figure 17-B.

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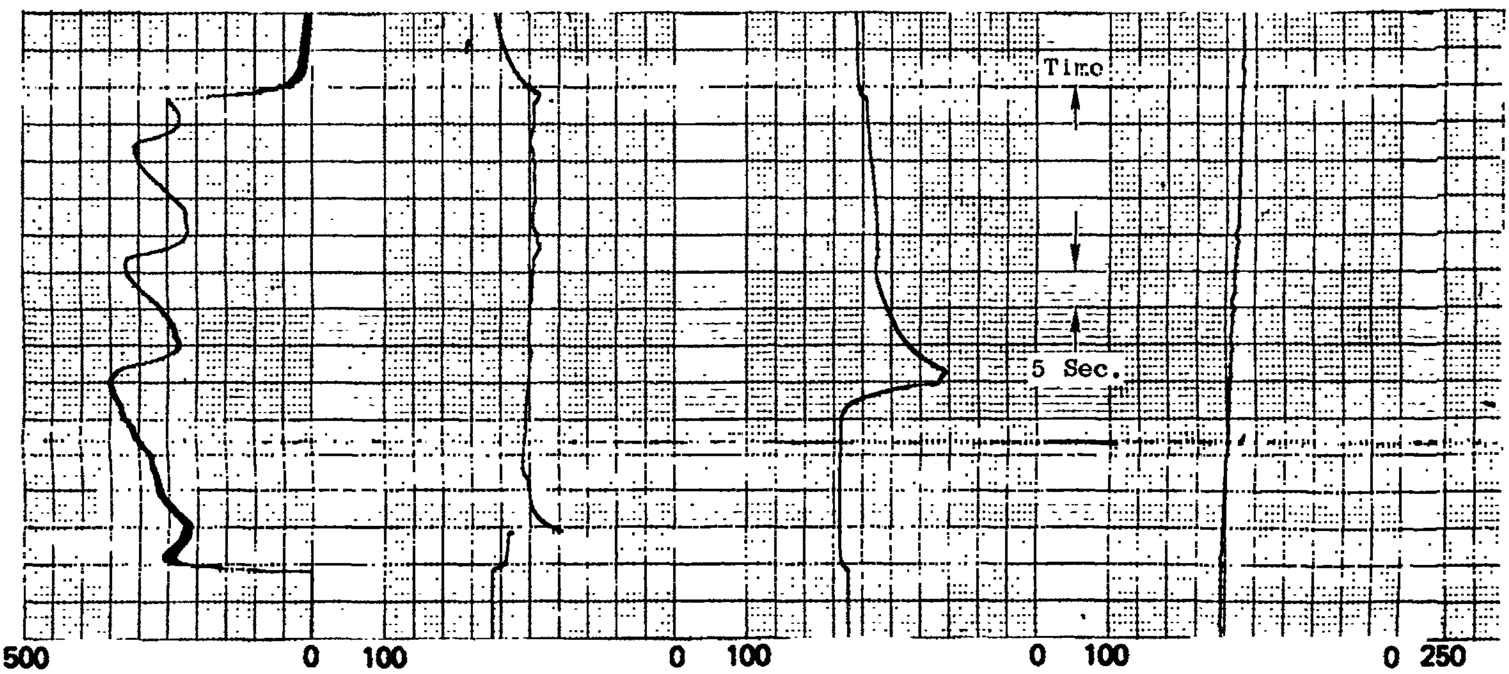

Thruster Force
lb x 10^{-3}

T_2 - Temperature at Output of Throttle Valve - ^oF

T_3 - Temperature at Heat Exchanger Output - ^oF

T_5 - Thruster Body Temperature - ^oF

P_1
In.

Alternating Liquid-Vapor Feed Data
(Starting with Liquid Feed - Switching Each 5 Seconds)

Figure 1

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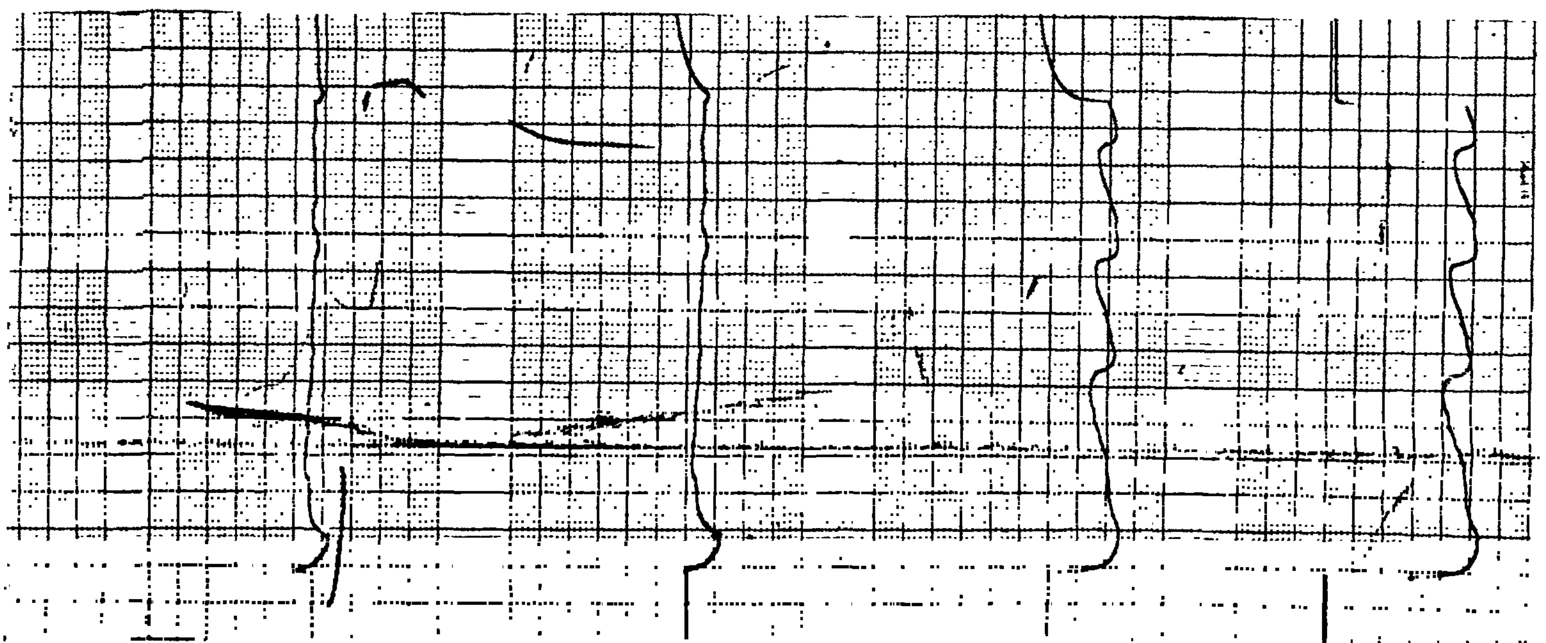

er Body
e - ^{o}F

P_1 - Pressure at Inlet to Throttle Valve - Psia

P_2 - Pressure at Outlet of Throttle Valve - Psia

P_3 - Pressure at Outlet of Heat Exchanger - Psia

P_4 - Thruster Nozzle Pressure - Psia

Feed Data
d -)
)

Propellant Fill Level 100%
Vacuum Tank Wall Temperature 75^{o}F
Storage Tank Temperature 69^{o}F

Figure 17-C.

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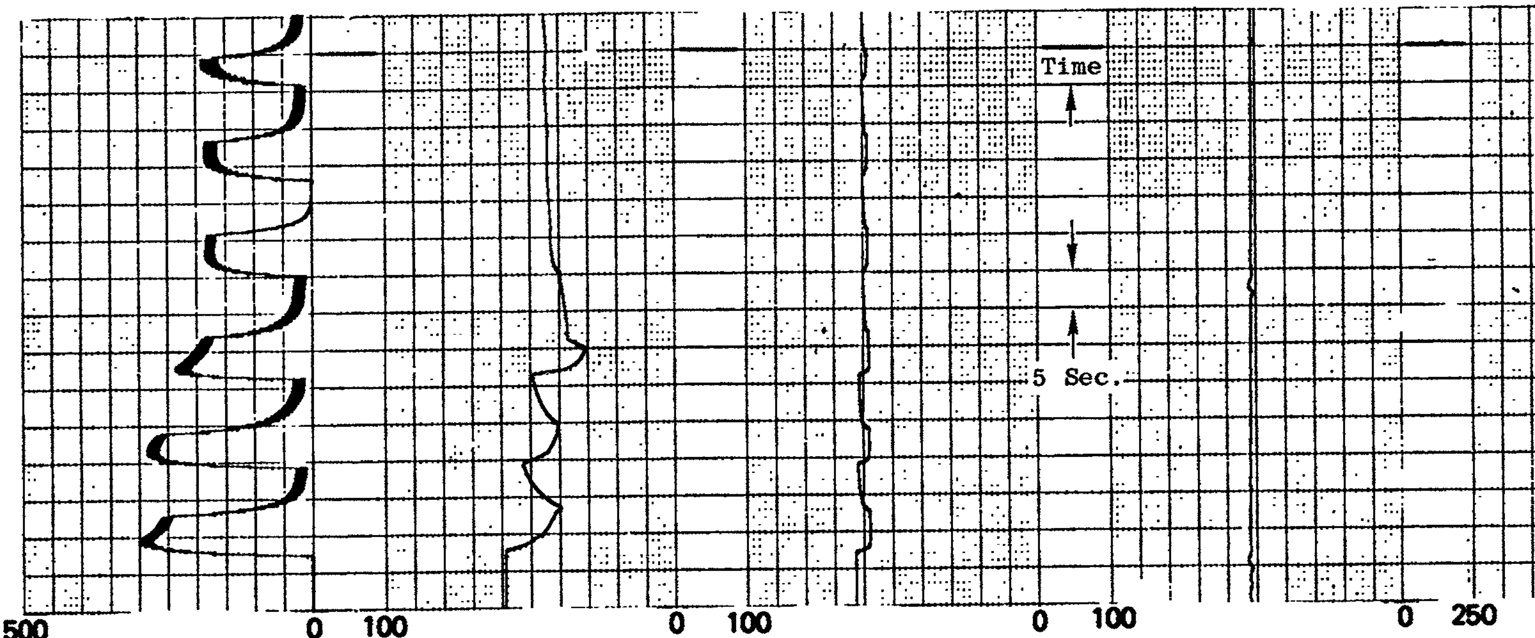
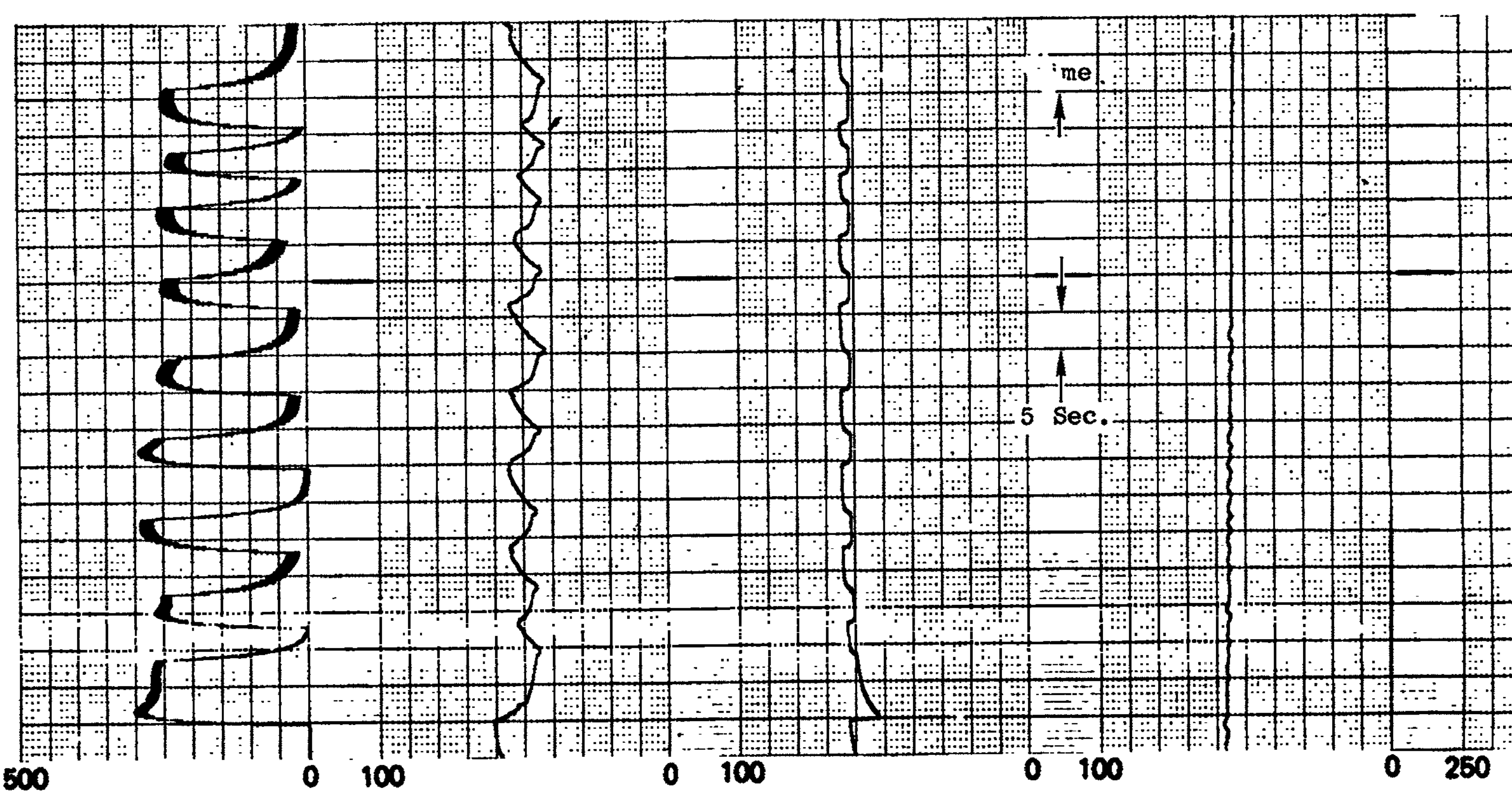


Thruster Force lb x 10^{-3} | T_2 - Temperature at Output of Throttle Valve - ^oF | T_3 - Temperature at Heat Exchanger Output - ^oF | T_5 - Thruster Body Temperature - ^oF | P_1 In.

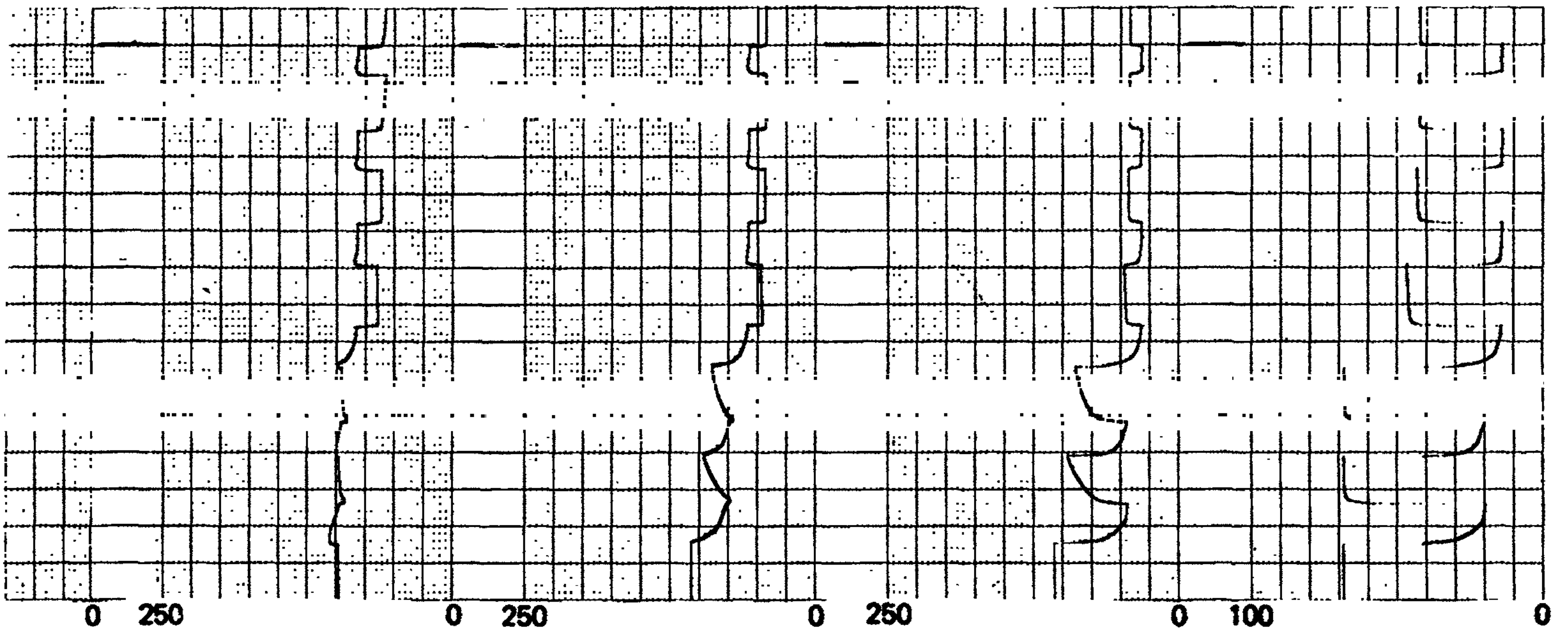
Vapor Feed Pulse Data { Propellant Fill Level 100% - Vacuum Tank W



Thruster Force lb x 10^{-3} | T_2 - Temperature at Output of Throttle Valve - ^oF | T_3 - Temperature at Heat Exchanger Output - ^oF | T_5 - Thruster Body Temperature - ^oF | P I

Liquid Feed Pulse Data { Propellant Fill Level 100% - Vacuum Tan

Figure 17-D



· Body - ^{o}F | P_1 - Pressure at Inlet to Throttle Valve - Psia | P_2 - Pressure at Outlet of Throttle Valve - Psia | P_3 - Pressure at Outlet of Heat Exchanger - Psia | P_4 - Thruster Nozzle Pressure - Psia

Vacuum Tank Wall Temperature 75°F - Storage Tank Temperature 59°F

er Body e - ^{o}F | P_1 - Pressure at Inlet to Throttle Valve - Psia | P_2 - Pressure at Outlet of Throttle Valve - Psia | P_3 - Pressure at Outlet of Heat Exchanger - Psia | P_4 - Thruster Nozzle Pressure - Psia

- Vacuum Tank Wall Temperature 75°F - Storage Tank Temperature 65°F

Figure 17-D.

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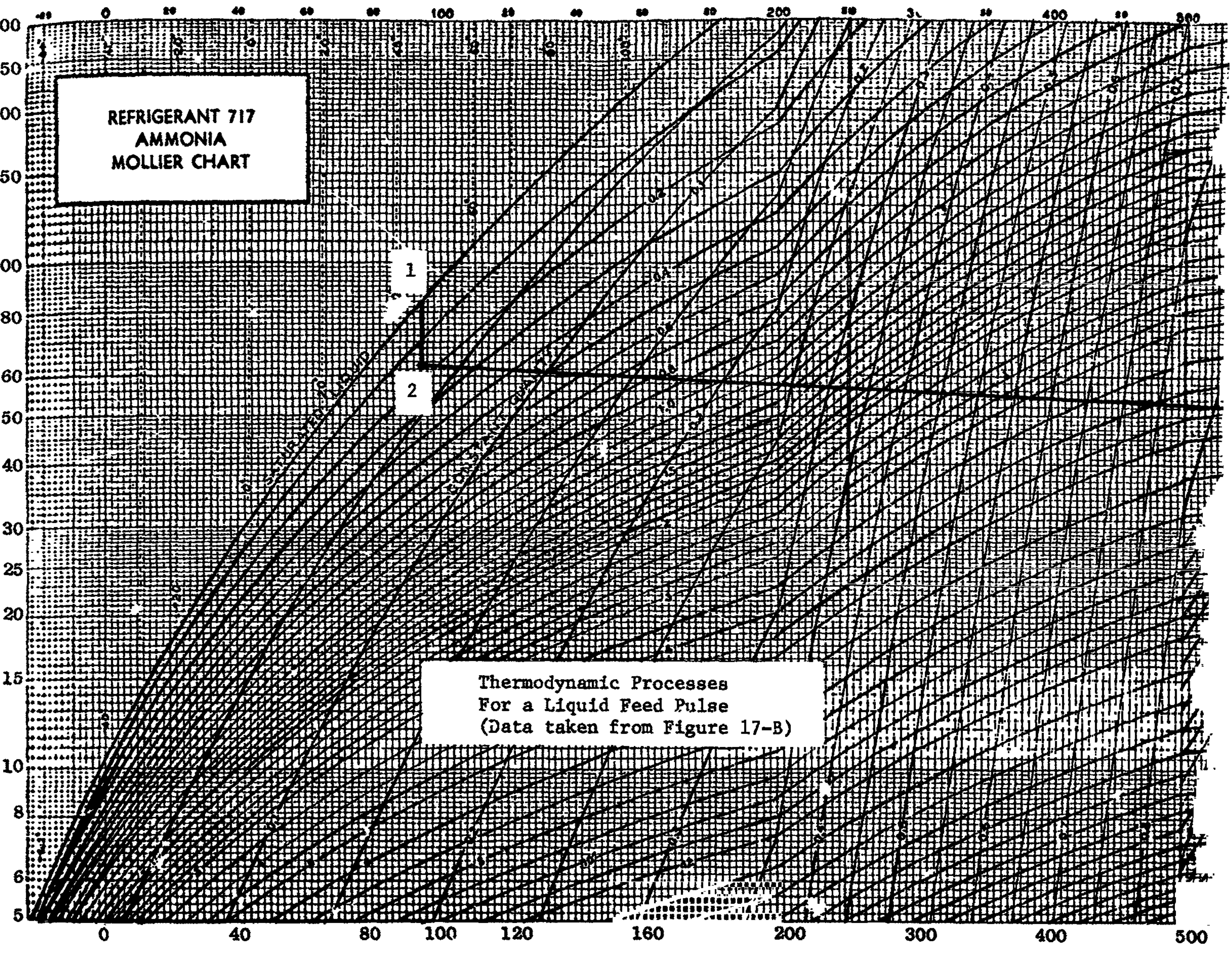

Pressure-Enthalpy Di

Figure 17-E

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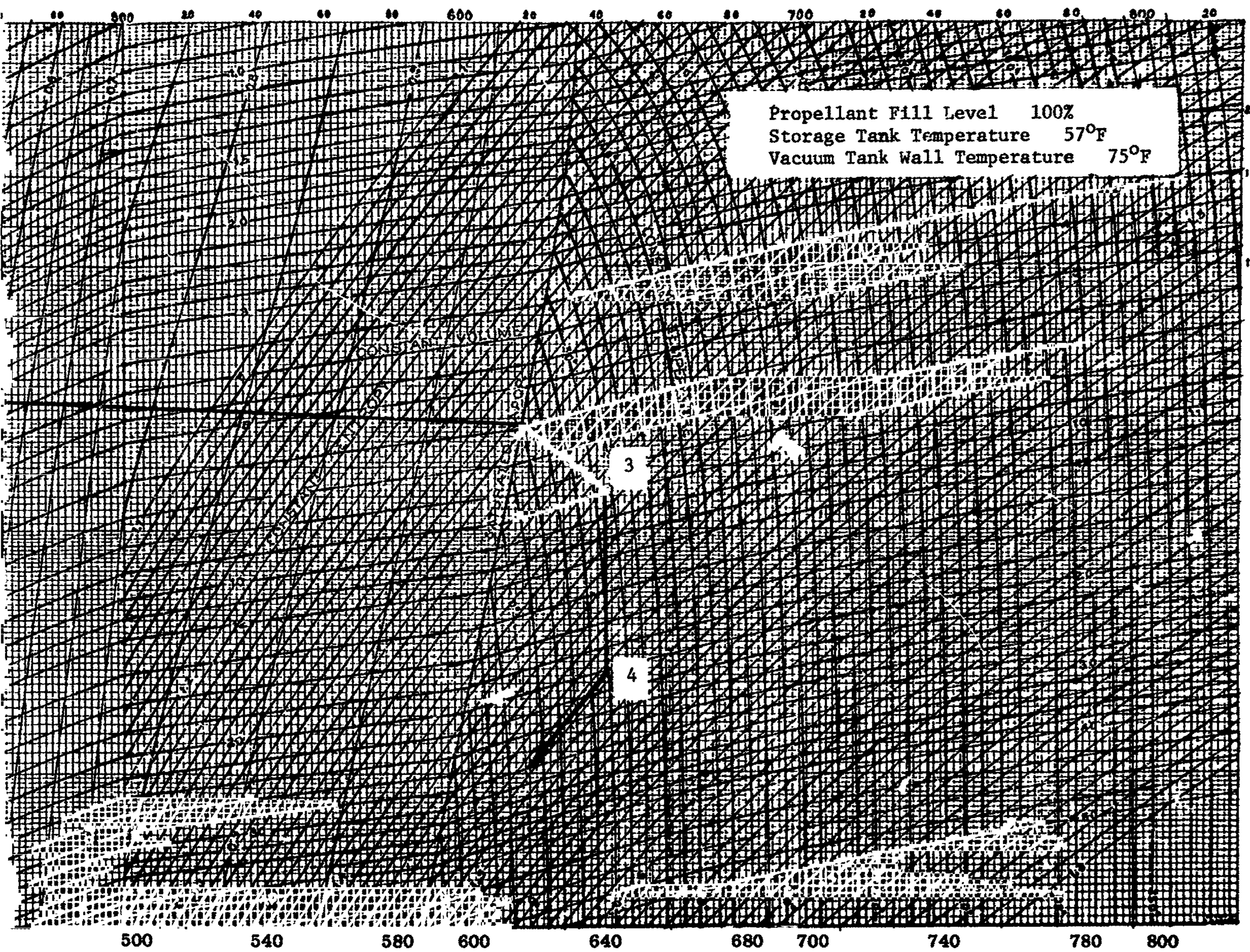
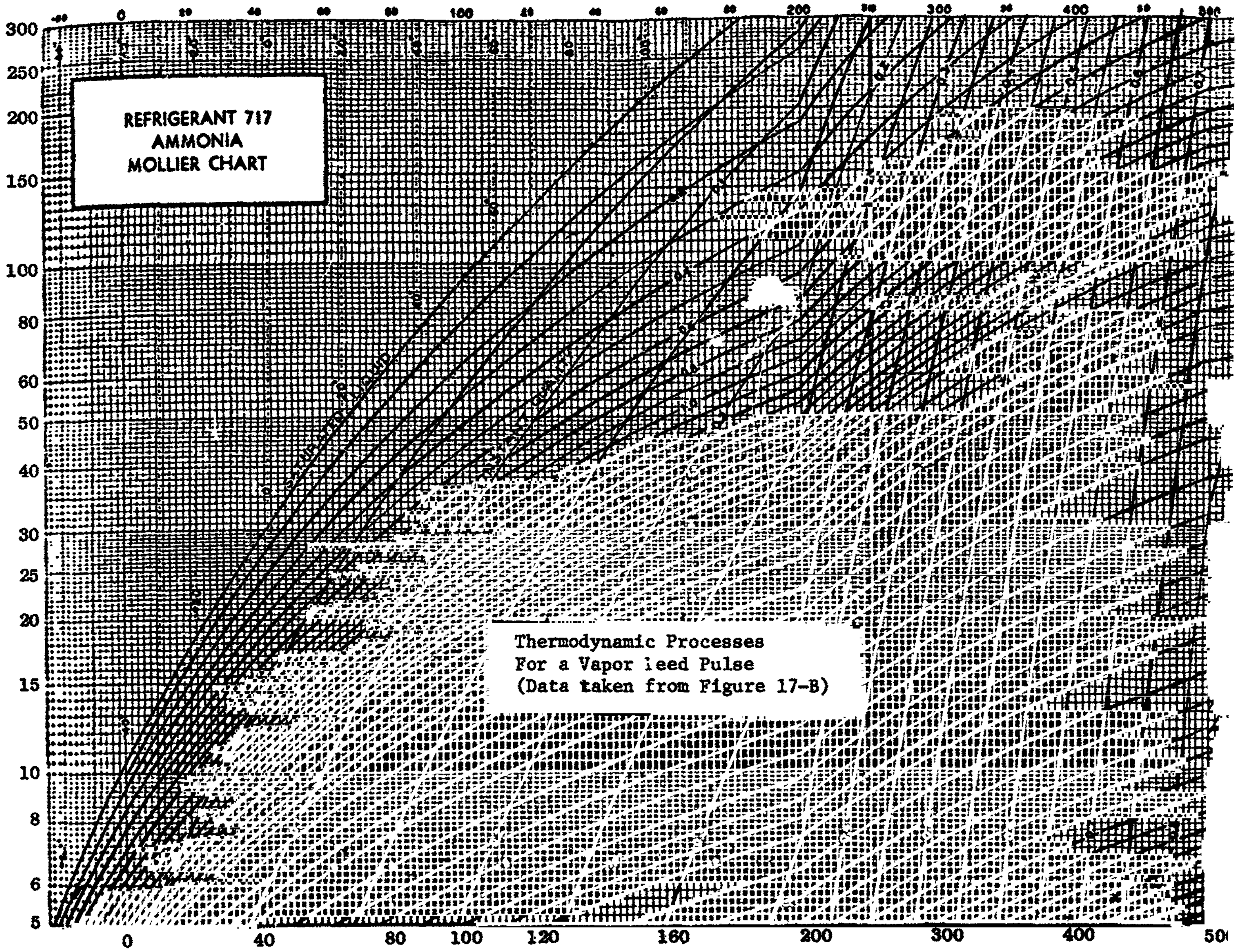


ure-Enthalpy Diagram

Heat Content - Btu. Per Lb.

Figure 17-E.



Pressure-Enthalpy D:

Figure 17-F.

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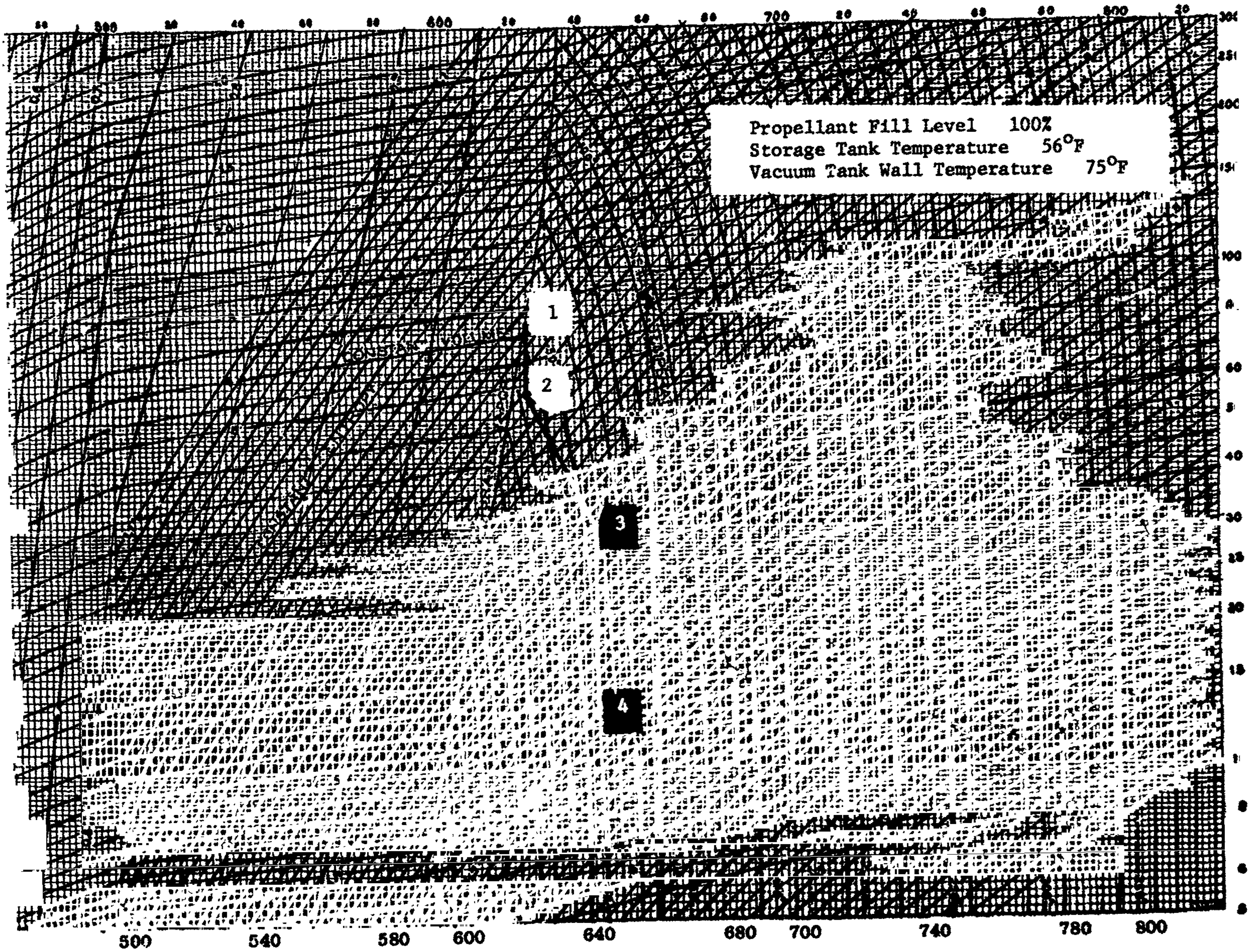


-Enthalpy Diagram

Figure 17-F.

FOLDOUT FRAME

In the liquid feed pulse data, the throttle valve performed as desired, maintaining an adequate pressure drop during periods of propellant flow, as indicated in Figures 17-A and 17-B, by the difference (P_1 - P_2). The temperature at the output of the throttle valve T_2 after an initial two or three second delay due to the sensible heat of the hardware, dropped satisfactorily 10-20°F, an entirely adequate temperature differential for effective heat transfer. The state of the ammonia at the throttle valve outlet is wet vapor. The quality varying with the isenthalpic pressure drop, is approximately 5%.

An examination of the temperature T_3 and pressure P_3, in Figures 17-A and 17-B, reveals the gas at the heat exchanger outlet to be highly supersaturated. For example, even when the propellant tank temperature is as low as 57°F, as in Figure 17-B, P_3 drops quickly to about 30 psia, corresponding to a saturated vapor temperature of 0°F, (See Figure 17-E.) but T_3 is about 56°F, indicating 56 degrees of superheat. In Figure 17-A, the worst combination of P_3 and T_3 is reached after about 19 seconds of thrusting. At this point P_3 is 44 psia corresponding to a saturated vapor temperature of about 17°F. Even here the value of T_3 is 64°F, corresponding to 47 degrees of superheat.

The process which the ammonia undergoes in the cycle from the storage tank through the system can be traced on the Mollier chart for ammonia given in Figure 17-E: first, the liquid ammonia is throttled from the tank to the inlet of the heat exchanger in an isenthalpic process. Second, the wet vapor undergoes two-phase boiling through a portion of the heat exchanger tubing, then superheat for the remainder of the tubing, exiting as superheated gas. Third, the superheated gas is isenthalpically expanded through the gas regulators. Finally, the gas experiences a nearly isentropic expansion through the thruster nozzle. The typical sequence shown on the chart is for the data from the second temperature stratum test.

The vapor feed pulse data show the expected decay patterns. In this mode of operation the system merely acts as a vapor superheater. The ammonia propellant undergoes several thermodynamic processes in the vapor feed mode. Saturated ammonia is expanded isenthalpically through the throttling valve. One phase gas superheats in the heat exchanger.

Superheated gas at the exit of the heat exchanger is isenthalpically expanded in the pressure regulator. The gas is expanded nearly isentropically through the thruster nozzle. Figure 17-F shows a typical case on a Mollier chart for the data from the second temperature stratum test.

Some important comparisons between the two modes of operation are appropriate. The general observation made when comparing the liquid feed pulse and the vapor feed pulse data of Figure 17-A is that the rate of decay of the pressures and temperatures is greatest when operating in the vapor feed mode. The rate of decline is basically dependent on the storage tank pressure and temperature. It is felt that the supply pressure P_1 drops most rapidly during the vapor feed mode for one or more of the following reasons:

a. The throttling valve may not be able to supply the required flow rate even when wide open. If this is the case, it could easily be demonstrated by flowing gaseous ammonia at various Δ P's across the throttling valve into a flow measuring device. Correction of this possible problem would also be simple - substitution of a high capacity throttle valve. However, if this were the problem, the pressure at the inlet to the throttle valve should not drop to the observed low value. Therefore, this factor alone cannot explain the observed behavior.

b. Since the gas generation rate depends on the liquid surface area, this may be a limiting factor in the gas pulse mode, the vaporization lagging the gas flow demand. If this were the only cause, the problem should exist at the beginning or middle of the pulse instead of only at the tail end, and the problem should be less severe when the tank is half full, exposing a larger surface area. Since neither of these phenomina are observed, this factor also cannot be entirely responsible.

c. The heat of vaporization required to supply the flow rate is being taken from the liquid ammonia sensible heat near the tank liquid-vapor interface, which may cause cooling of the liquid surface and a commensurate reduction in its vapor pressure. Conductive and/or convective heat transfer may not be rapid enough to eliminate the temperature variation in the liquid. In contrast, during the liquid f[illegible] mode, the heat of vaporization needed to sustain the propellant mass flow rate is still drawn mainly (a very small amount of radiant heat is utilized) from the liquid ammonia sensible heat. But this is through the heat exchanger, which covers the entire tank, giving a larger transient sensible heat sink source.

Figure 17-B is presented to relate the system performance at the same fill level (100%) but at the second storage tank temperature stratum (56 - 57°F). The shapes of the curves are the same as before at the higher temperature stratum, but are naturally at pressure and temperature values commensurate with the lower temperature stratum The thruster performance has fallen due to the nozzle pressure P_4 dropping below the design value of 22 psia. Since the pressure at the outlet of the heat exchanger is in all cases higher than this value, the use of a higher capacity and better quality regulator should eliminate this problem.

Figure 17-C is presented to show the behavior of the system when operating with alternating liquid vapor feed (simulating a zero-g) propellant slosh condition). The vapor and liquid solenoid valves, SV-1 and SV-2, were switched at 5-second intervals to change the throttle valve input fluid from vapor to liquid. In figure 17-C, the important thing to note is the relatively small perturbations caused when the switch is made from liquid to vapor and vice versa. This shows that the throttling valve adjusts its flow area rapidly and satisfactorily to accommodate either type of propellant flow. The large variations in the thruster output are again due to the fluctuations in P_4, due to the regulator.

Figure 17-D is presented to show the behavior of the system when executing several short (5 sec) duration pulses. The repeatability of the pulses is good for the liquid feed pulses. The vapor feed pulses are affected by the characteristic rapid drop in supply pressure P_1.

The specific impulse developed by the thrusters was within the predicted range. The data allow one to determine very quickly the value of the effective specific impulse by the following steps:

1. Note the value of F_t
2. Note the value of P_4 occurring simultaneously with F_t.
3. Convert the P_4 pressure value to nozzle weight flow rate via the nozzle calibration curve, Section V-P.

4. Make the following calculation: $I_{sp} = \frac{F_t}{\dot{W}}$

When this is done for the data presented herein, the effective impulse varies between 77 and 85 seconds. If the tests were being run in a space vacuum where the ambient pressure would be zero pressure, the values would be approximately 10-15% higher (this is based on the data of Section V-M).

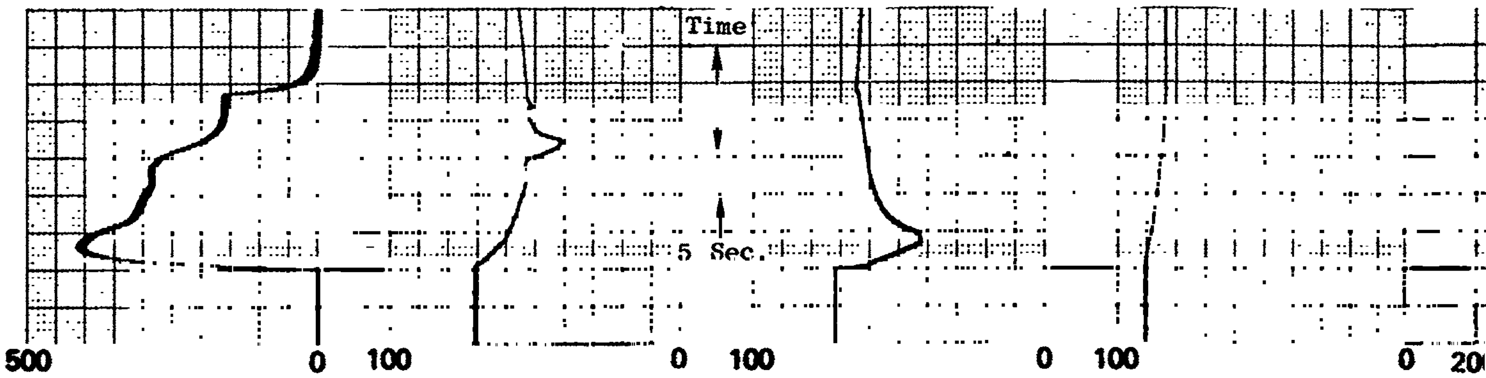
All the previous discussion has been centered on the 100% fill level tests for the room ambient and second temperature strata. Data for the 75%, 50%, and 25% fill levels are given in Figures 18, 19, and 20. The variation of these data from the 100% fill level data is not significant.

G. TECHNICAL SUMMARY AND RECOMMENDATIONS

TECHNICAL SUMMARY

A prototype passive vaporizing liquid ammonia feed system with attitude control thrusters has been designed, fabricated and performance tested. The feed system utilized a tubular heat exchanger-vaporizer coupled with a two phase throttling valve concept to perform the vaporization to liquid ammonia. The concept was tested for continuous, pulsed, and alternating liquid and vapor flow over a range of propellant storage temperatures. In the liquid feed mode, the operation was entirely satisfactory, except for the pressure regulator, which kept the thruster chamber pressure above rather than at the desired pressure. In the vapor feed mode, the propellants supply pressure dropped more than expected, but still supplied the required pressure for success if a better pressure regulator was used downstream of the heat exchanger.

Despite the above problems, the program demonstrated the feasibility and workability of utilizing spacecraft waste thermal heat resources to supply the substantial latent heat of vaporization of the liquid ammonia. The largest source of heat for the feed system operation was the sensible heat of the liquid ammonia stored in the propellant tank. During the operation of the system the temperature of the propellant storage tank diminished as sensible heat was extracted. The system can be operated in a continuous mode or a pulse mode until the decline in the tank



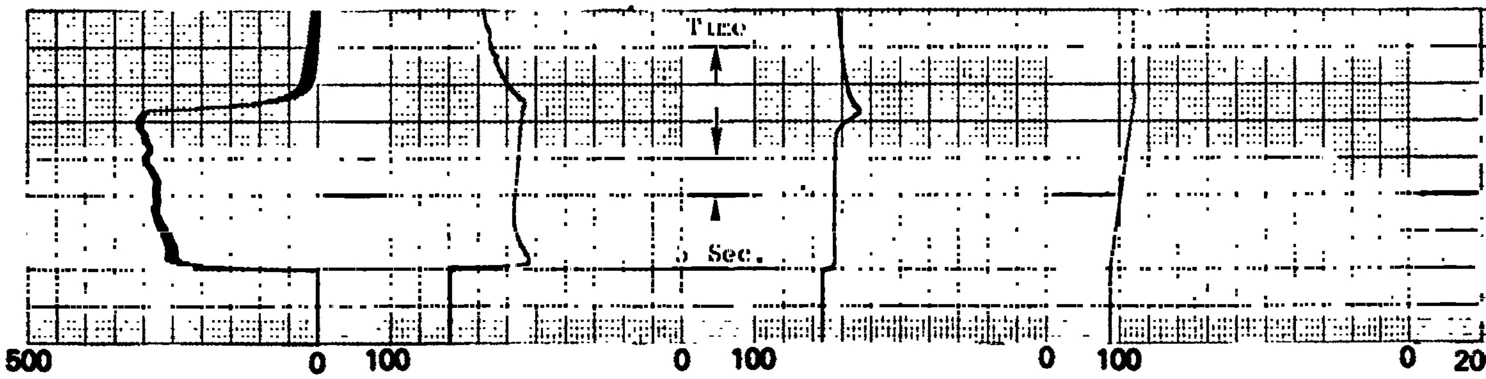
Thruster Force
lb x 10^{-3}

T_2 - Temperature at
Output of Throttle
Valve - ^oF

T_3 - Temperature at
Heat Exchanger
Output - ^oF

T_5 - Thruster Body
Temperature - ^oF

Vapor Feed Pulse Data { Propellant
Vacuum Tan
Storage Ta



Thruster Force
lb x 10^{-3}

T_2 - Temperature at
Output of Throttle
Valve - ^oF

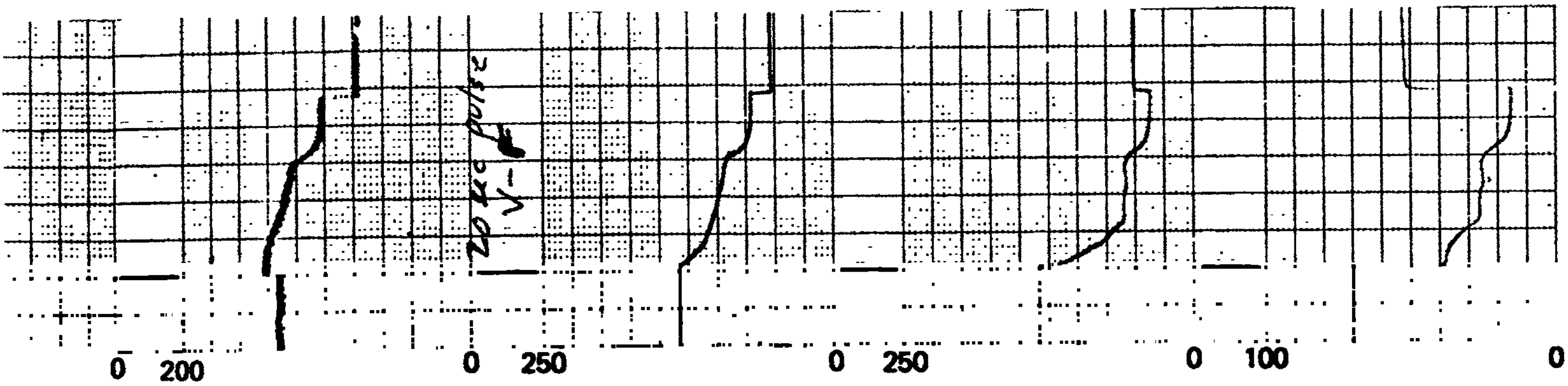
T_3 - Temperature at
Heat Exchanger
Output - ^oF

T_5 - Thruster Body
Temperature - ^oF

Liquid Feed Pulse Data { Propellant
Vacuum Ta
Storage T

Figure 18-A

FOLDOUT FRAME



ter Body
re - ^{o}F

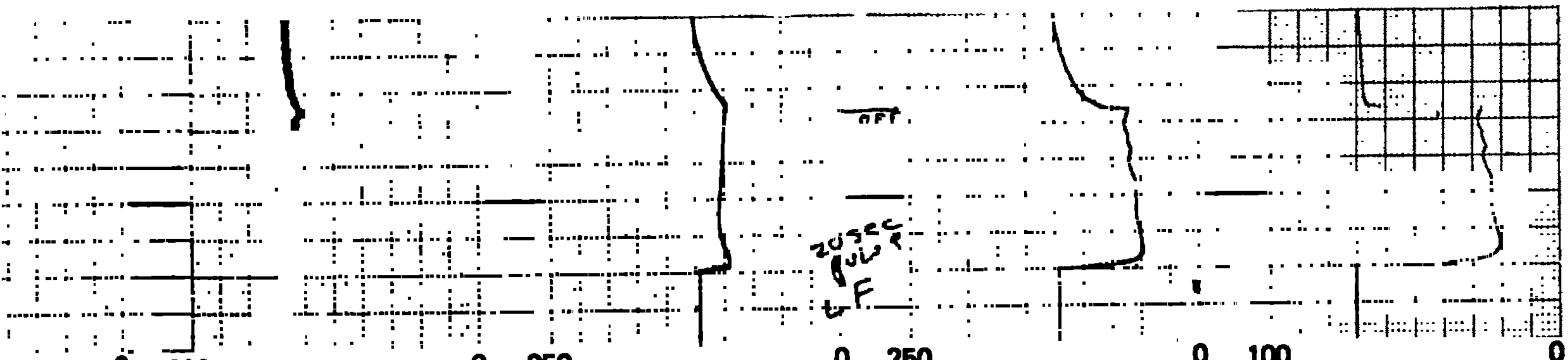
P_1 - Pressure at Inlet to Throttle Valve - Psia

P_2 - Pressure at Outlet of Throttle Valve - Psia

P_3 - Pressure at Outlet of Heat Exchanger - Psia

P_4 - Thruster Nozzle Pressure - Psia

Propellant Fill Level 75%
Vacuum Tank Wall Temperature 75^{o}F
Storage Tank Temperature 70^{o}F



ter Body
re - ^{o}F

P_1 - Pressure at Inlet to Throttle Valve - Psia

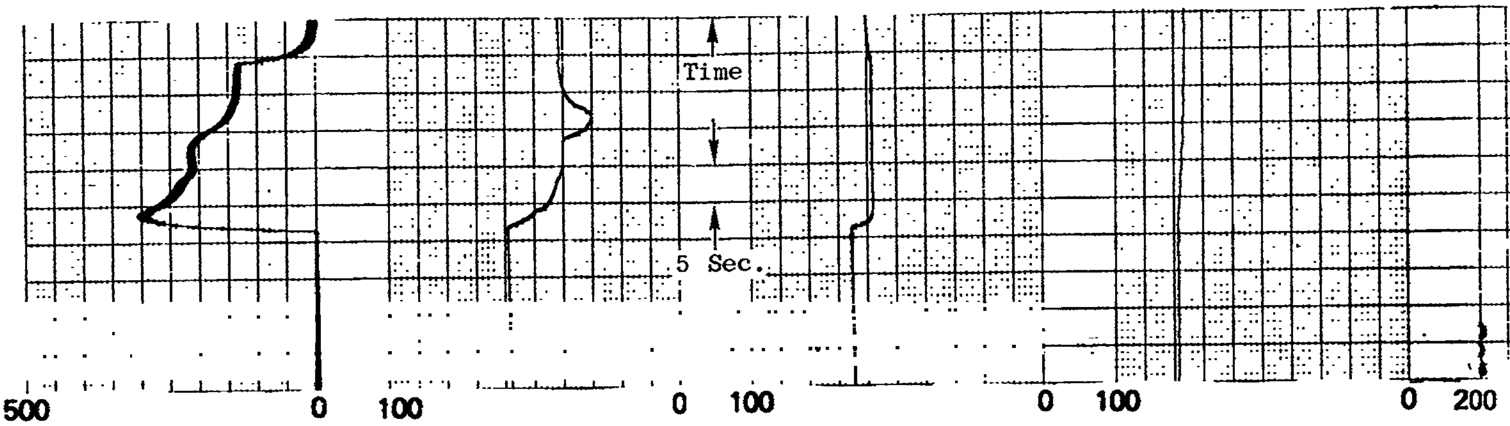
P_2 - Pressure at Outlet of Throttle Valve - Psia

P_3 - Pressure at Outlet of Heat Exchanger - Psia.

P_4 - Thruster Nozzle Pressure - Psia

Propellant Fill Level 75%
Vacuum Tank Wall Temperature 75^{o}F
Storage Tank Temperature 75^{o}F

Figure 18-A.



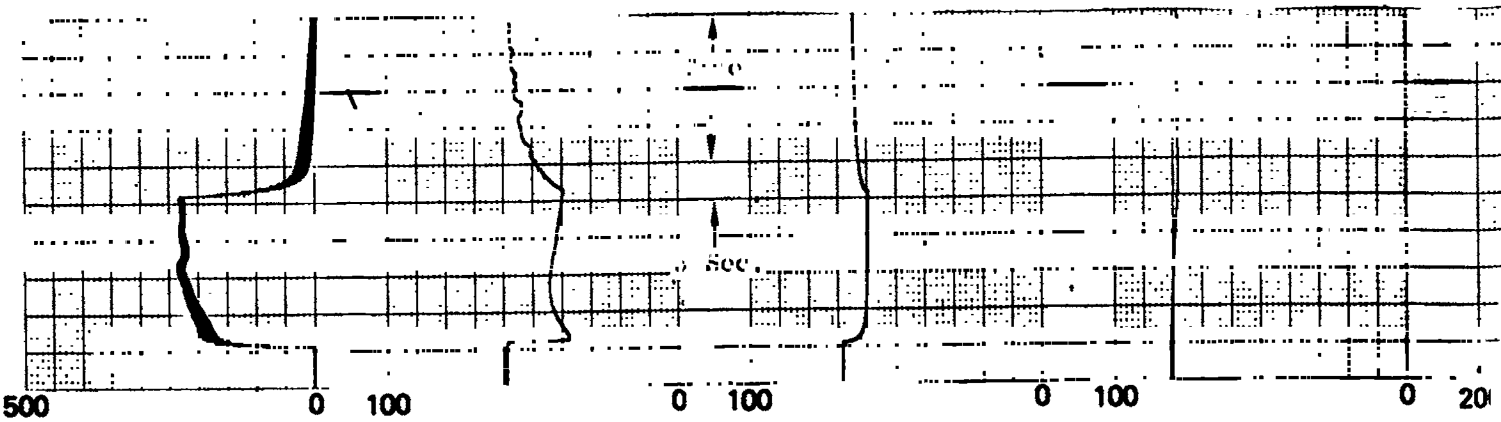
Thruster Force
lb x 10^{-3}

T_2 - Temperature at Output of Throttle Valve - ^oF

T_3 - Temperature at Heat Exchanger Output - ^oF

T_5 - Thruster Body Temperature - ^oF

Vapor Feed Pulse Data { Propellan
Vacuum T
Storage



Thruster Force
lb x 10^{-3}

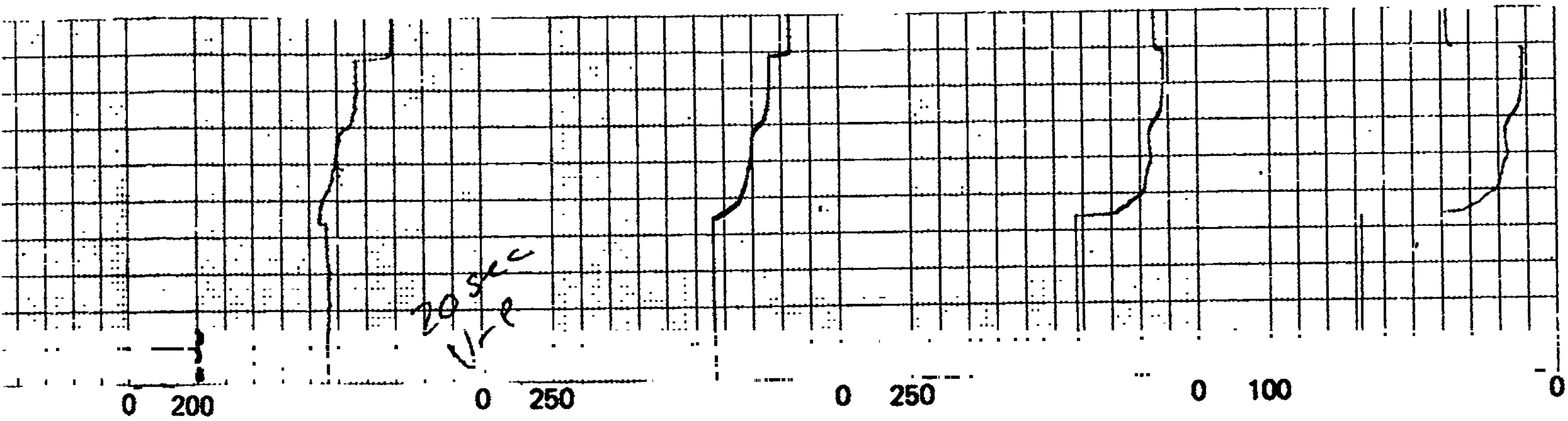
T_2 - Temperature at Output of Throttle Valve - ^oF

T_3 - Temperature at Heat Exchanger Output - ^oF

T_5 - Thruster Body Temperature - ^oF

Liquid Feed Pulse Data { Propellan
Vacuum T
Storage

Figure 18-



ster Body
re - ^{o}F

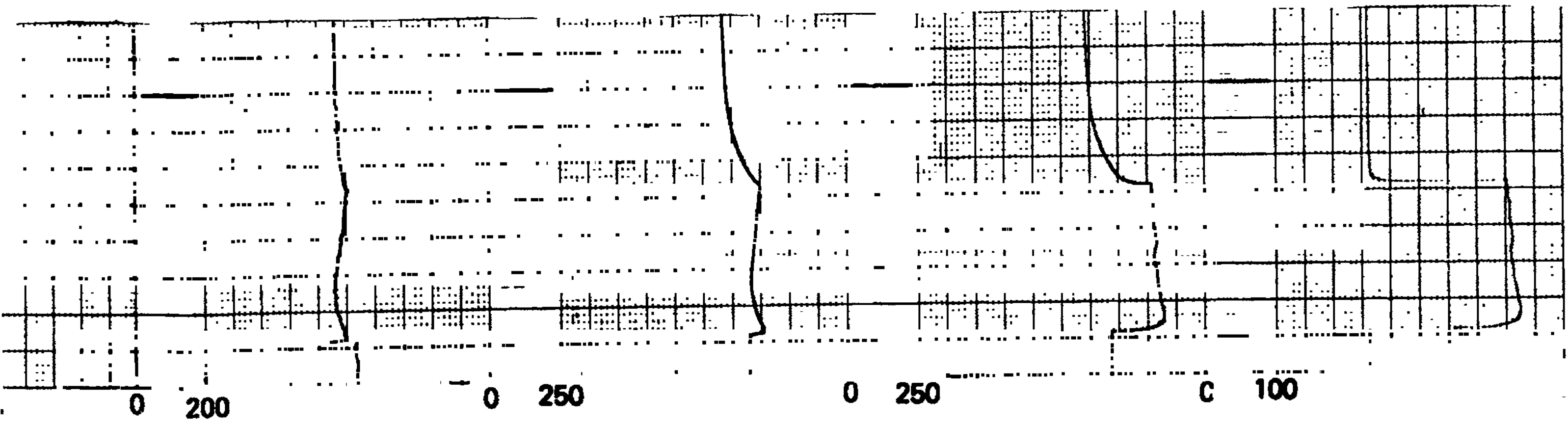
P_1 - Pressure at Inlet to Throttle Valve - Psia

P_2 - Pressure at Outlet of Throttle Valve - Psia

P_3 - Pressure at Outlet of Heat Exchanger - Psia

P_4 - Thruster Nozzle Pressure - Psia

ta { Propellant Fill Level 75%
Vacuum Tank Wall Temperature 75^{o}F
Storage Tank Temperature 60^{o}F



ster Body
ure - ^{o}F

P_1 - Pressure at Inlet to Throttle Valve - Psia

P_2 - Pressure at Outlet of Throttle Valve - Psia

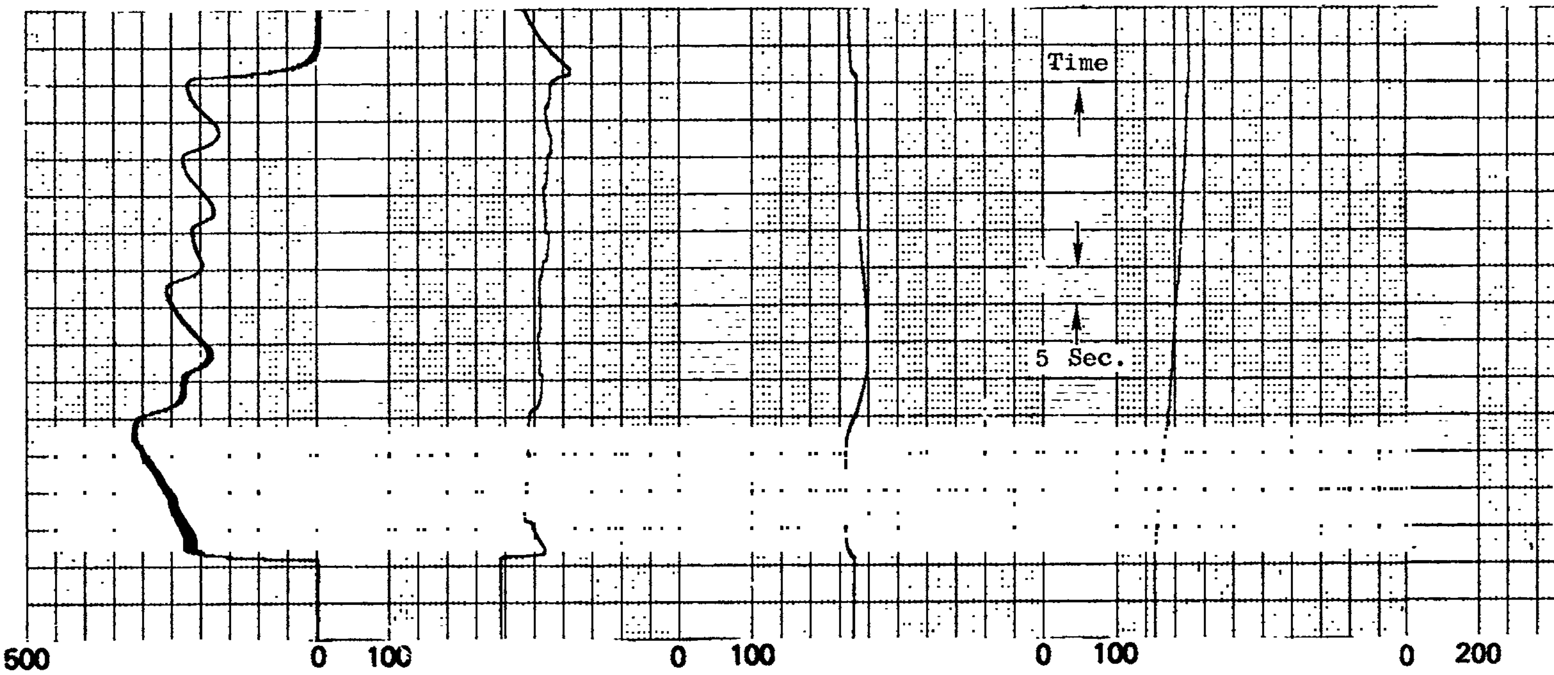
P_3 - Pressure at Outlet of Heat Exchanger - Psia

P_4 - Thruster Nozzl Pressure - Psia

ta { Propellant Fill Level 75%
Vacuum Tank Wall Temperature 75^{o}F
Storage Tank Temperature 62^{o}F

Figure 18-B.

FOLDOUT FRAME



Thruster Force
lb x 10^{-3}

T_2 - Temperature at
Output of Throttle
Valve - ^oF

T_3 - Temperature at
Heat Exchanger
Output - ^oF

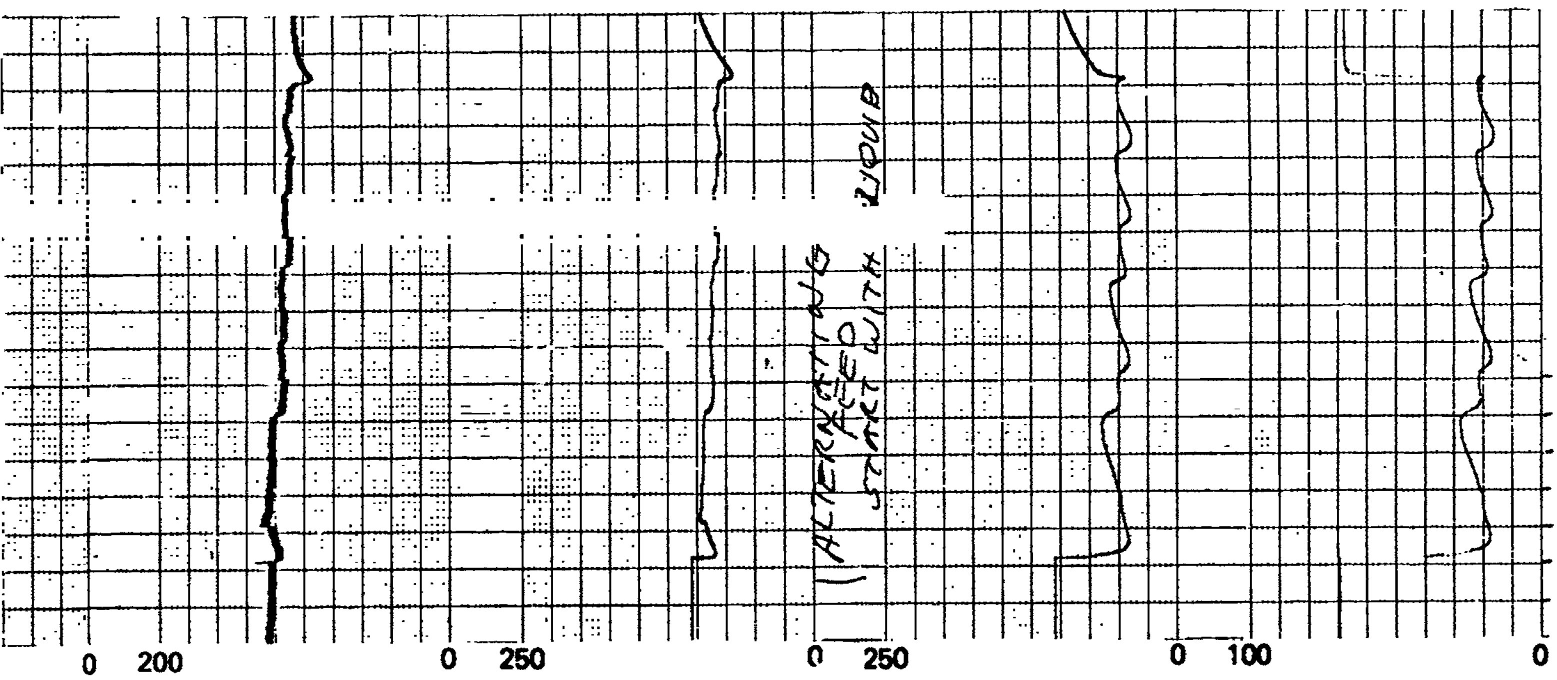
T_5 - Thruster Body
Temperature - ^oF

P_1
Inl
V

Alternating Liquid-Vapor Feed Data { Propell
Vacuum
Storage

Figure 18-C.

DOUT FRAME



r Body
- $^{\circ}F$

P_1 - Pressure at Inlet to Throttle Valve - Psia

P_2 - Pressure at Outlet of Throttle Valve - Psia

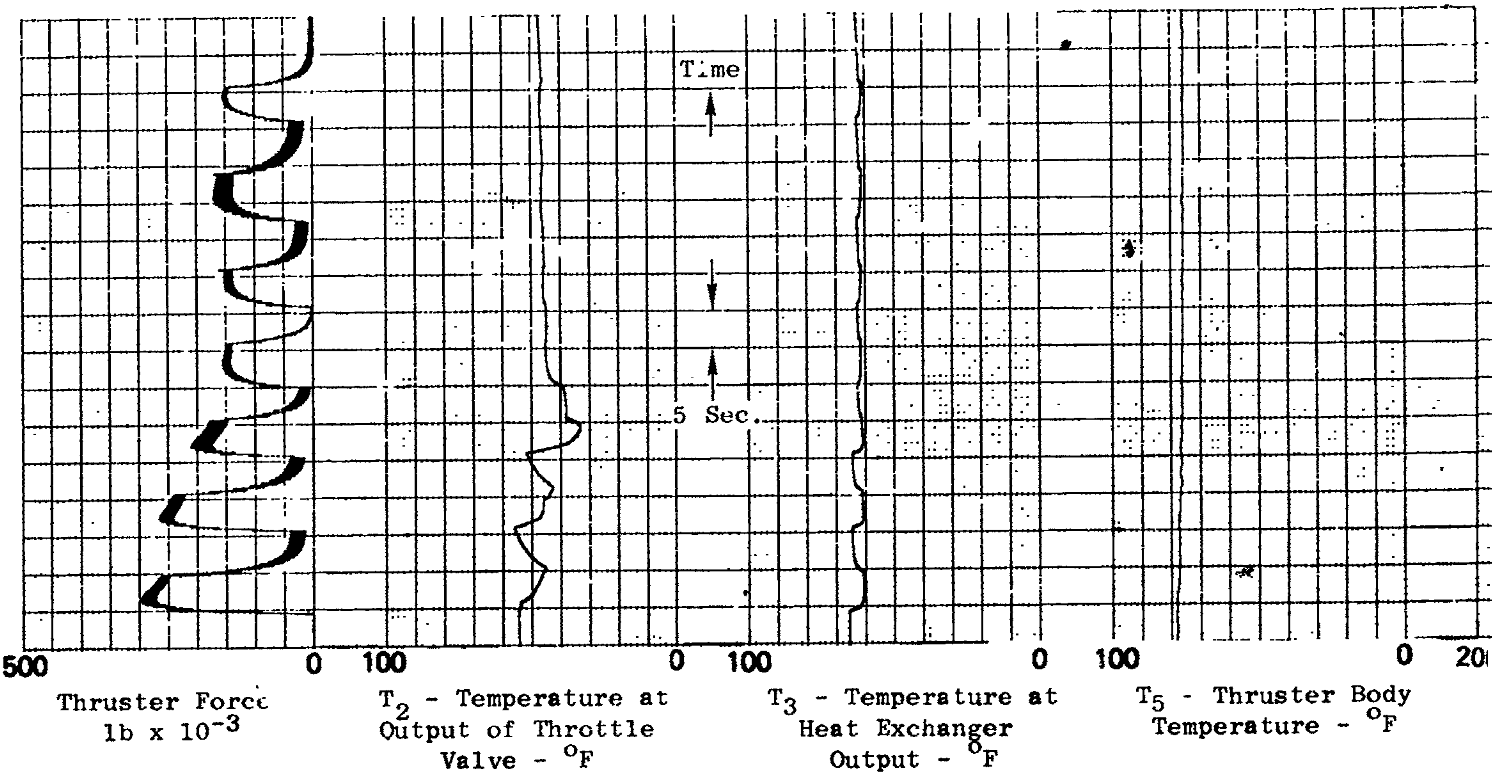
P_3 - Pressure at Outlet of Heat Exchanger - Psia

P_4 - Thruster Nozzle Pressure - Psia

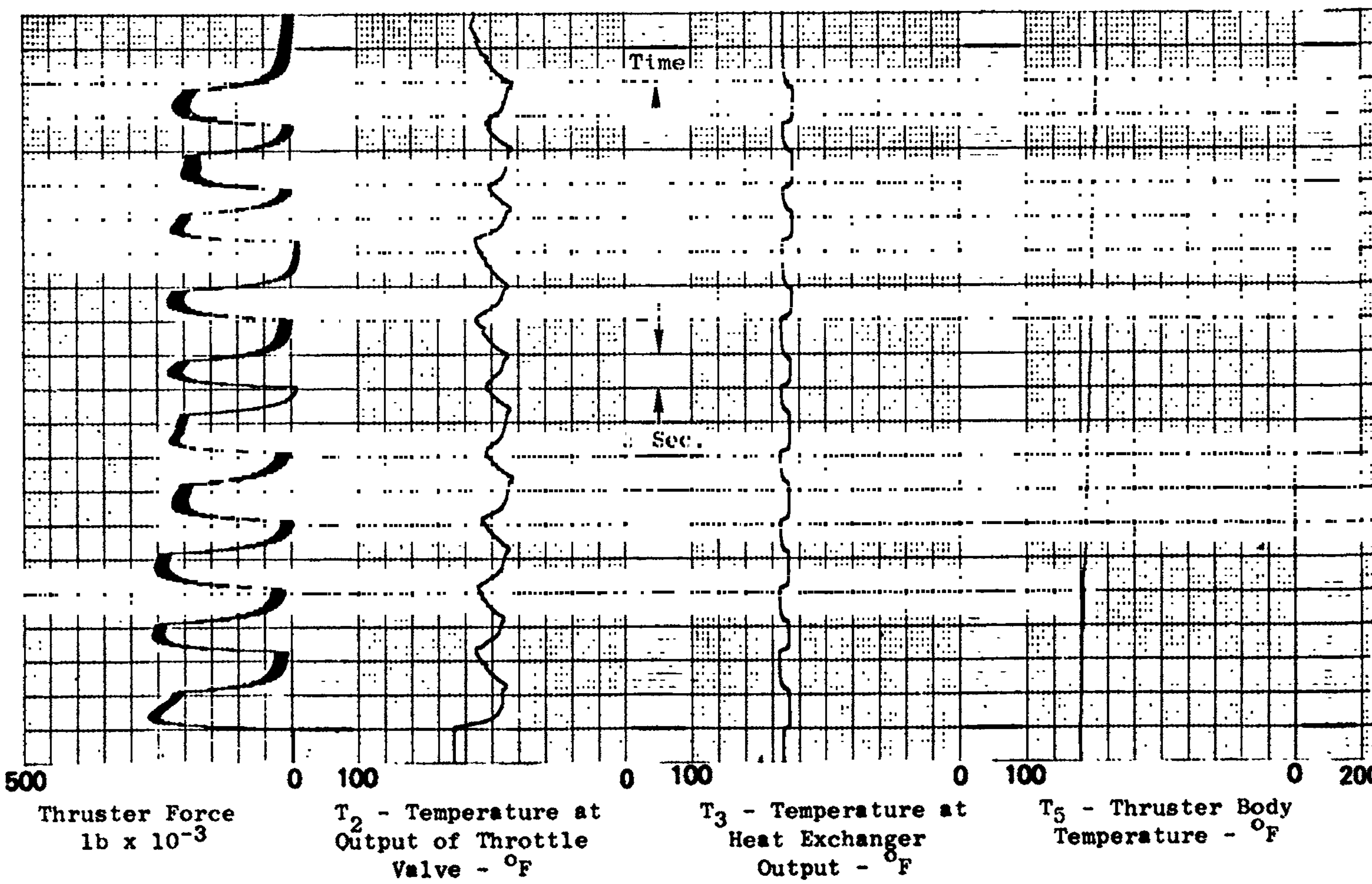
ata { Propellant Fill Level 75%
Vacuum Tank Wall Temperature 75°F
Storage Tank Temperature 71°F

Figure 18-C.

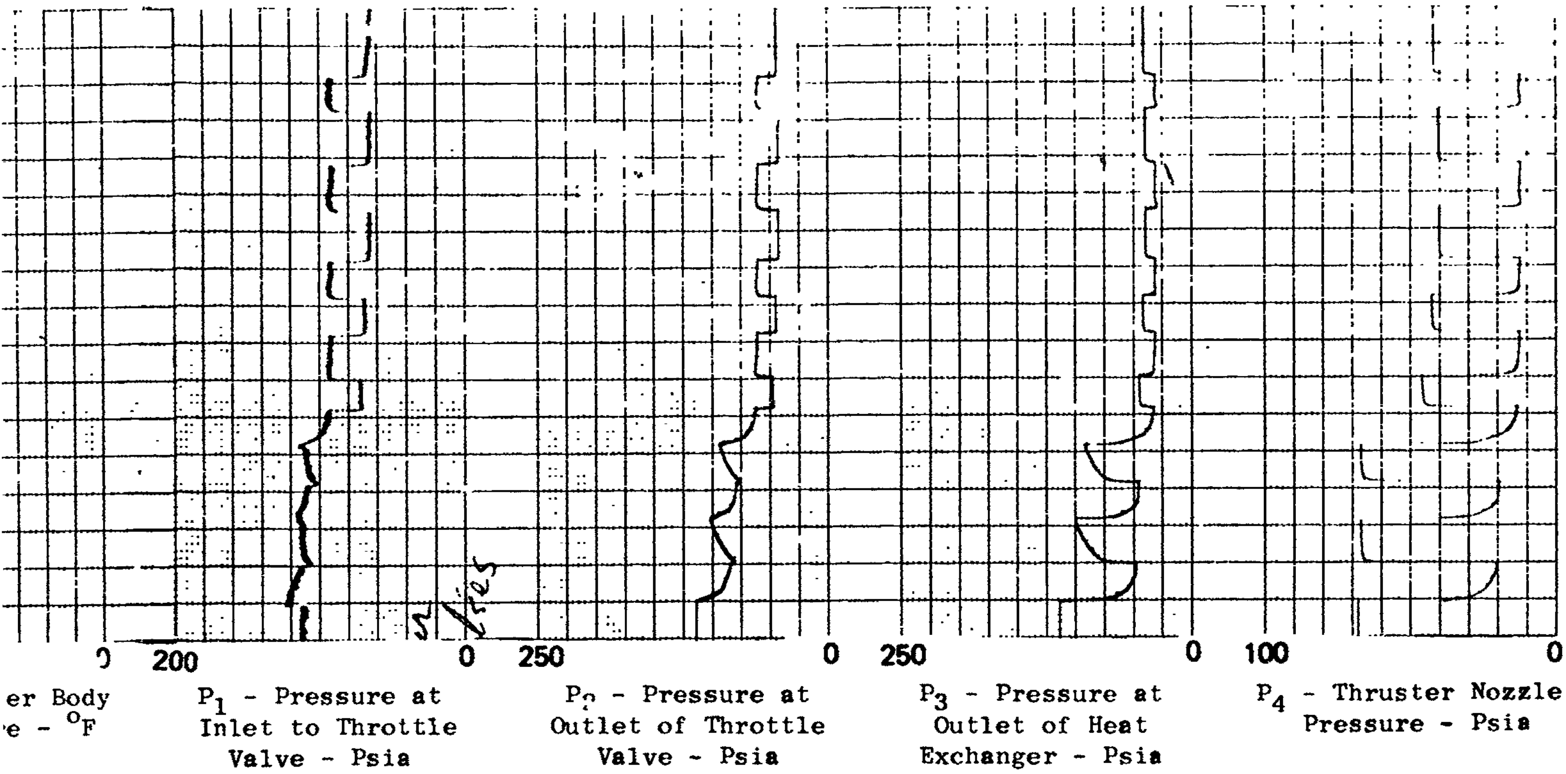
FOLDOUT FRAME



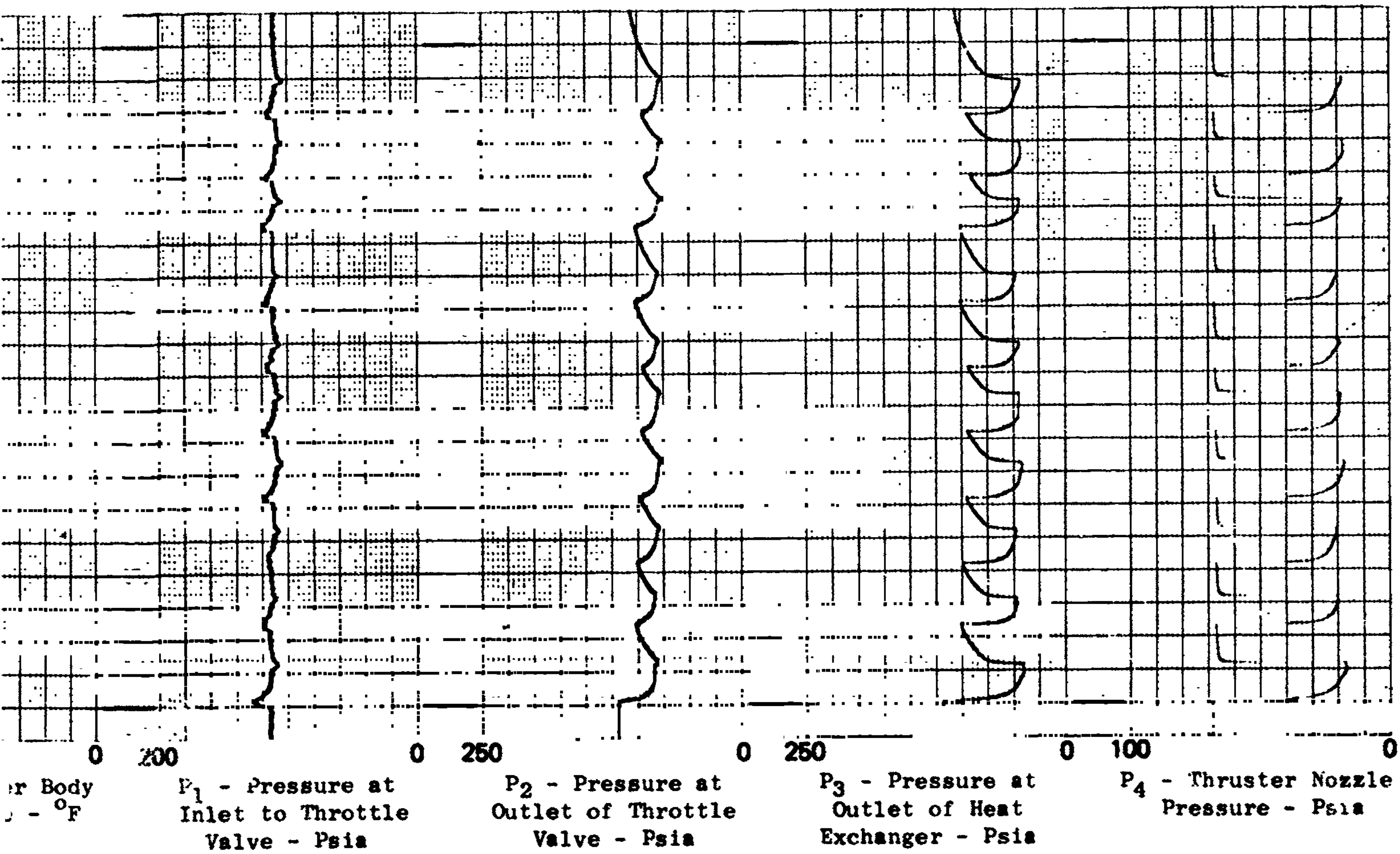
Vapor Feed Pulse Data { Propella
Vacuum T
Storage



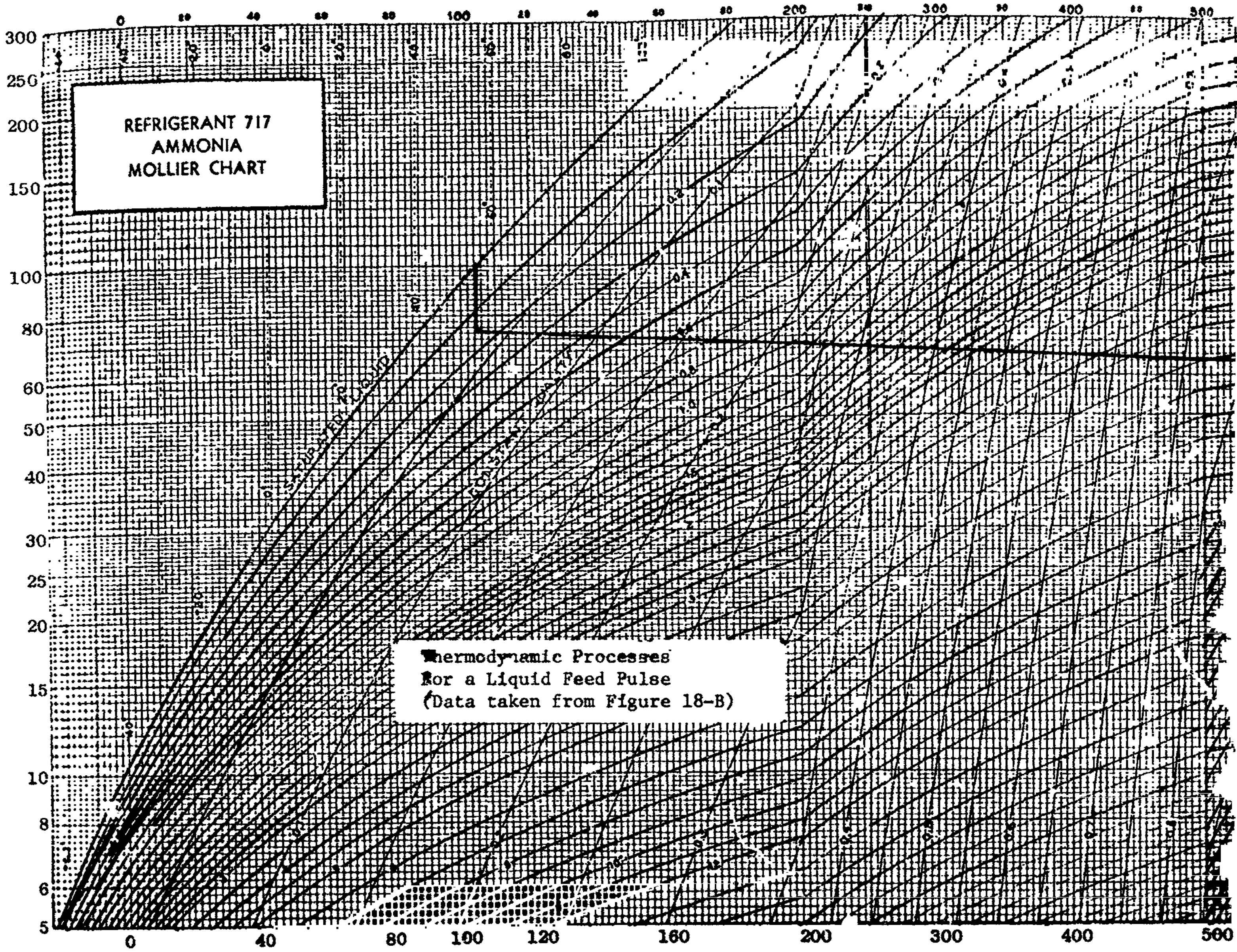
Liquid Feed Pulse Data { Propel
Vacuum
Stora



Propellant Fill Level 75%
Vacuum Tank Wall Temperature 75°F
Storage Tank Temperature 64°F



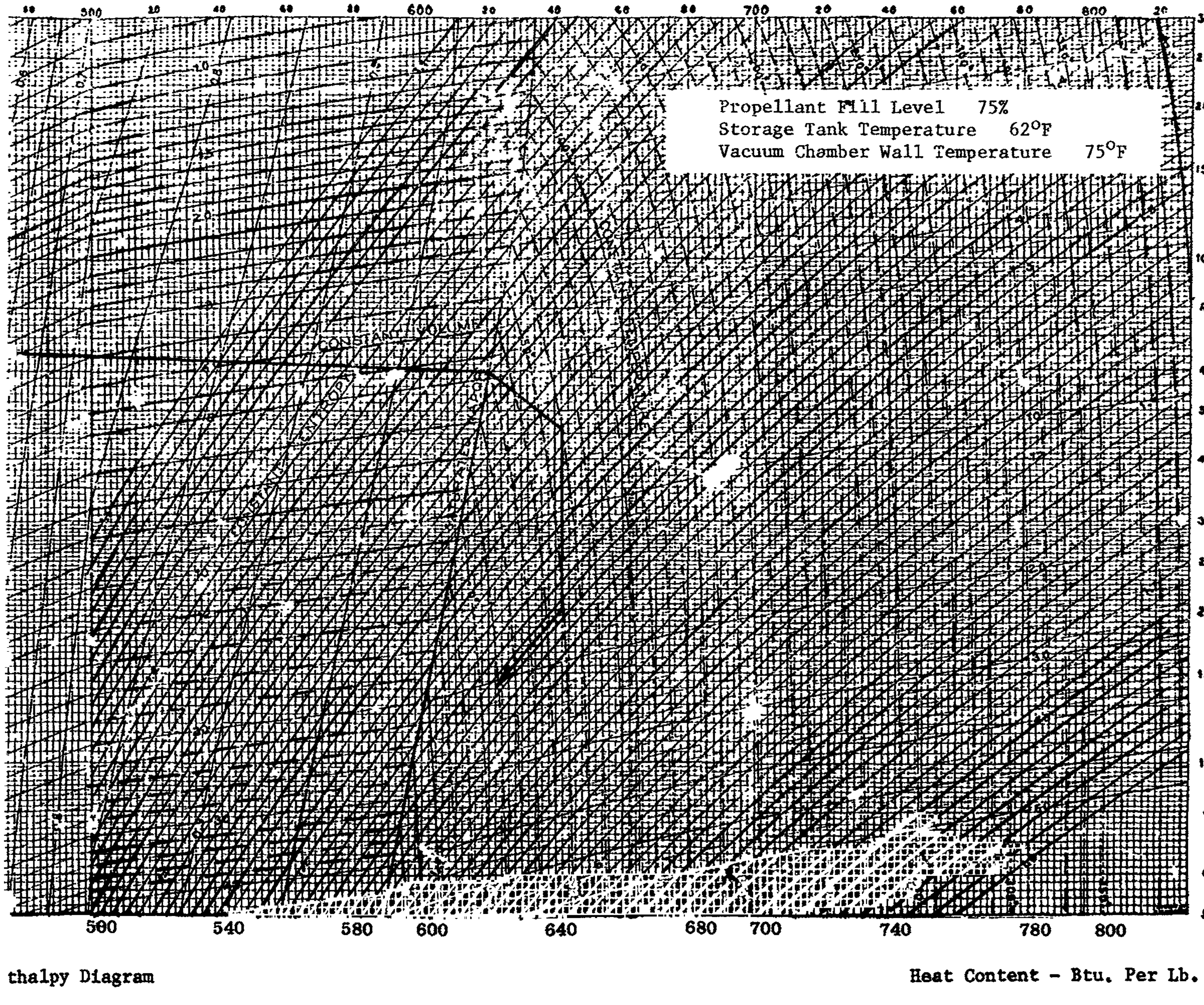
:a
Propellant Fill Level 75%
Vacuum Tank Wall Temperature 75°F
Storage Tank Temperature 67°F



Pressure-Enthalpy Dia

Figure 18-E.

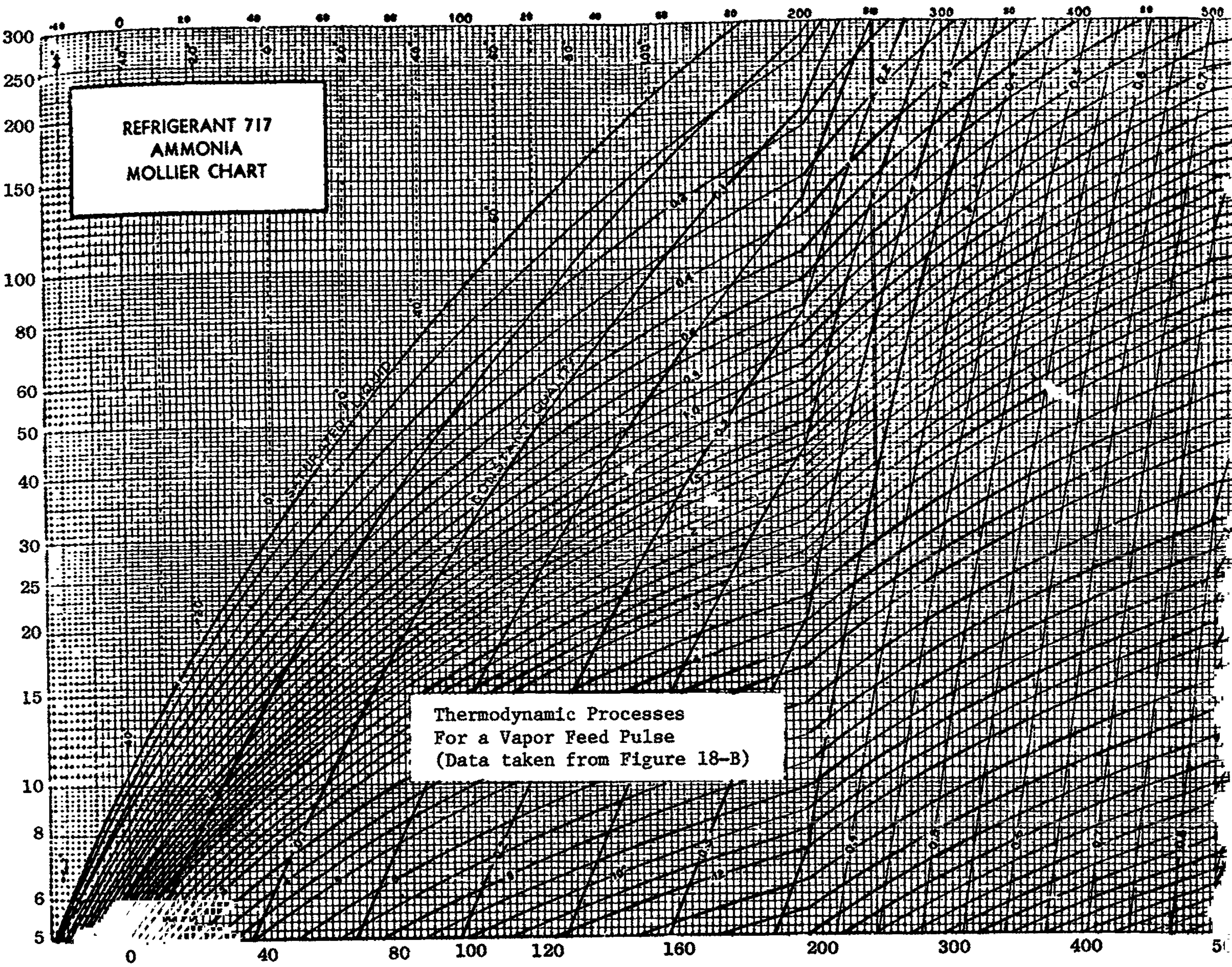
FOLDOUT FRAME



thalpy Diagram

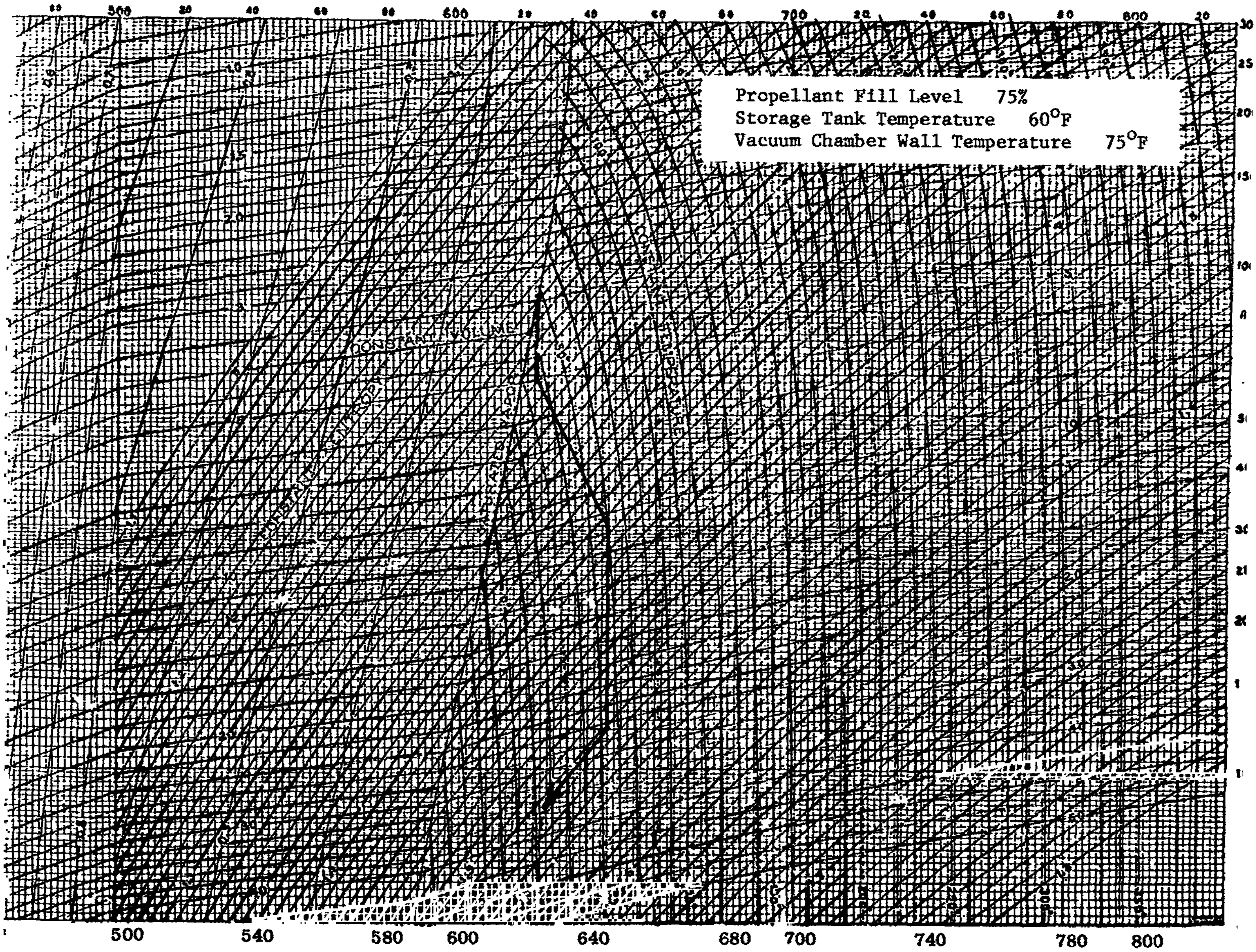
Heat Content - Btu. Per Lb.

igure 18-E.



Pressure-Enthalpy

Figure 18-F

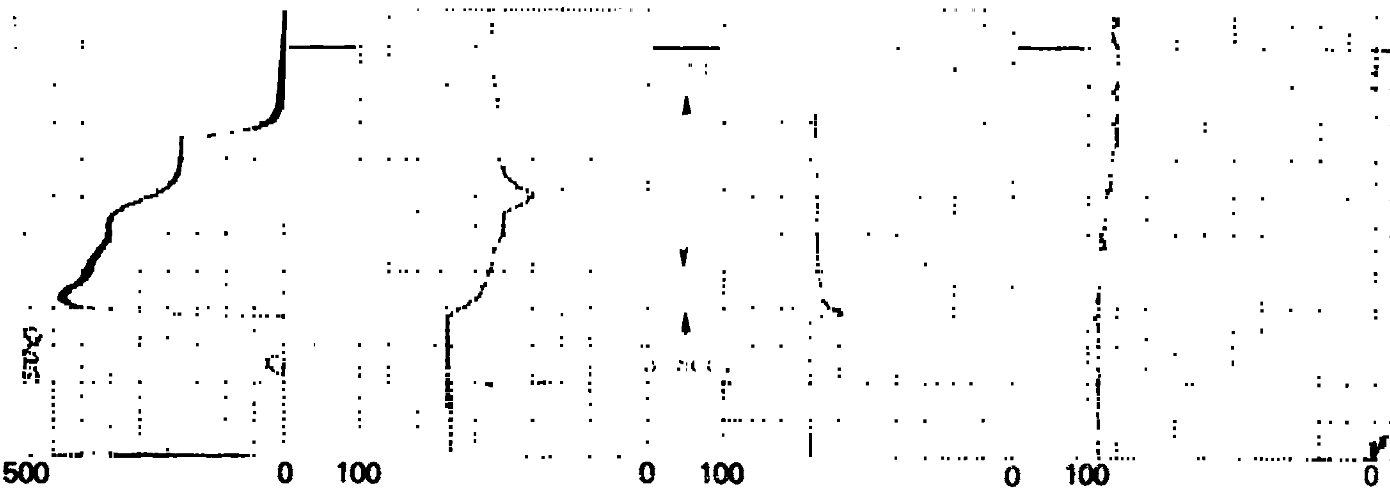


re-Enthalpy Diagram

Heat Content - Btu- Per Lb.

Figure 18-F.

FOLDOUT FRAME



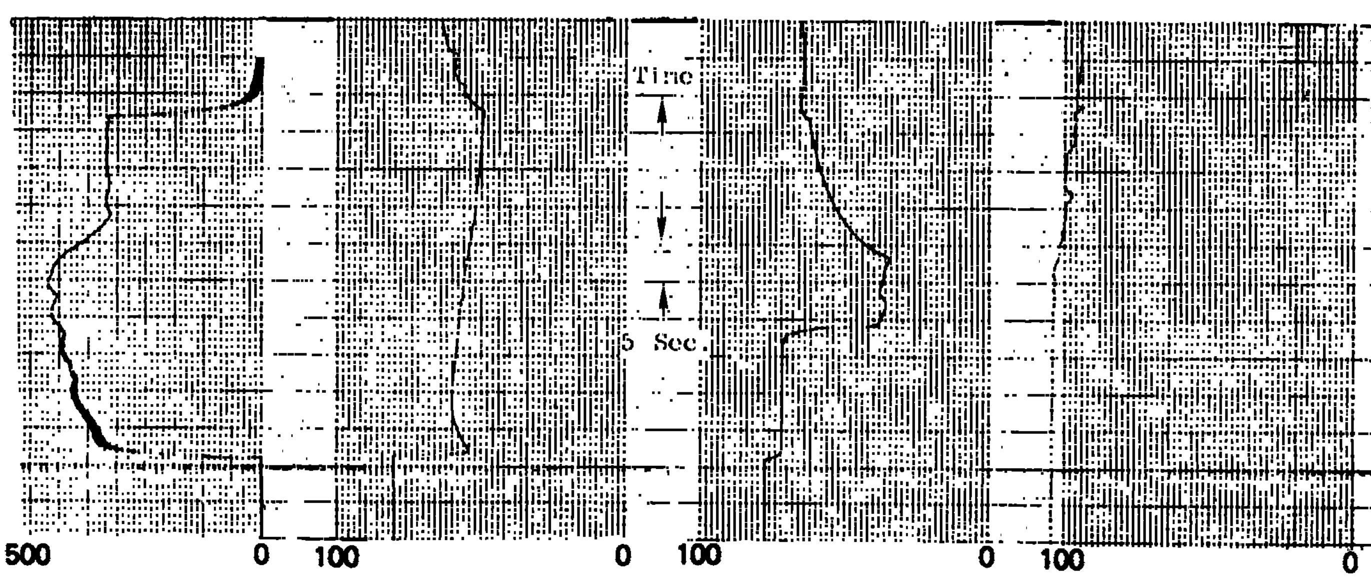
Thruster Force
lb x 10^{-3}

T_2 - Temperature at Output of Throttle Valve - ^oF

T_3 - Temperature at Heat Exchanger Output - ^oF

T_5 - Thruster Body Temperature - ^oF

Vapor Feed Pulse Data



Thruster Force
lb x 10^{-3}

T_2 - Temperature at Output of Throttle Valve - ^oF

T_3 - Temperature at Heat Exchanger Output - ^oF

T_5 - Thruster Body Temperature - ^oF

Liquid Feed Pulse Data

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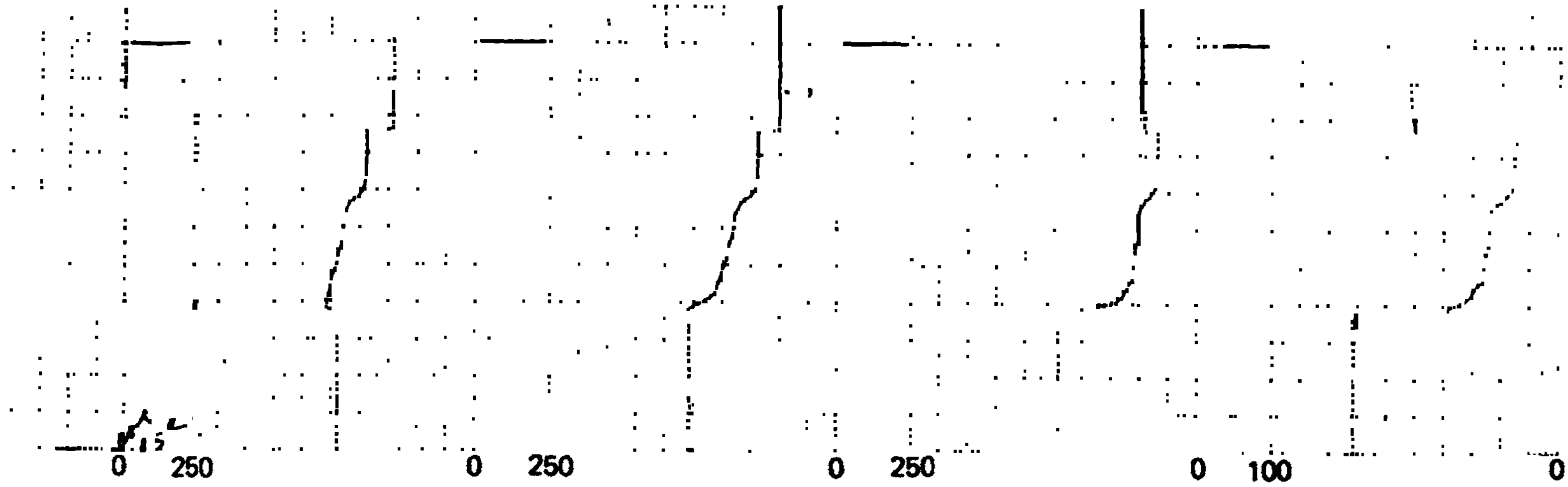
Figure 1

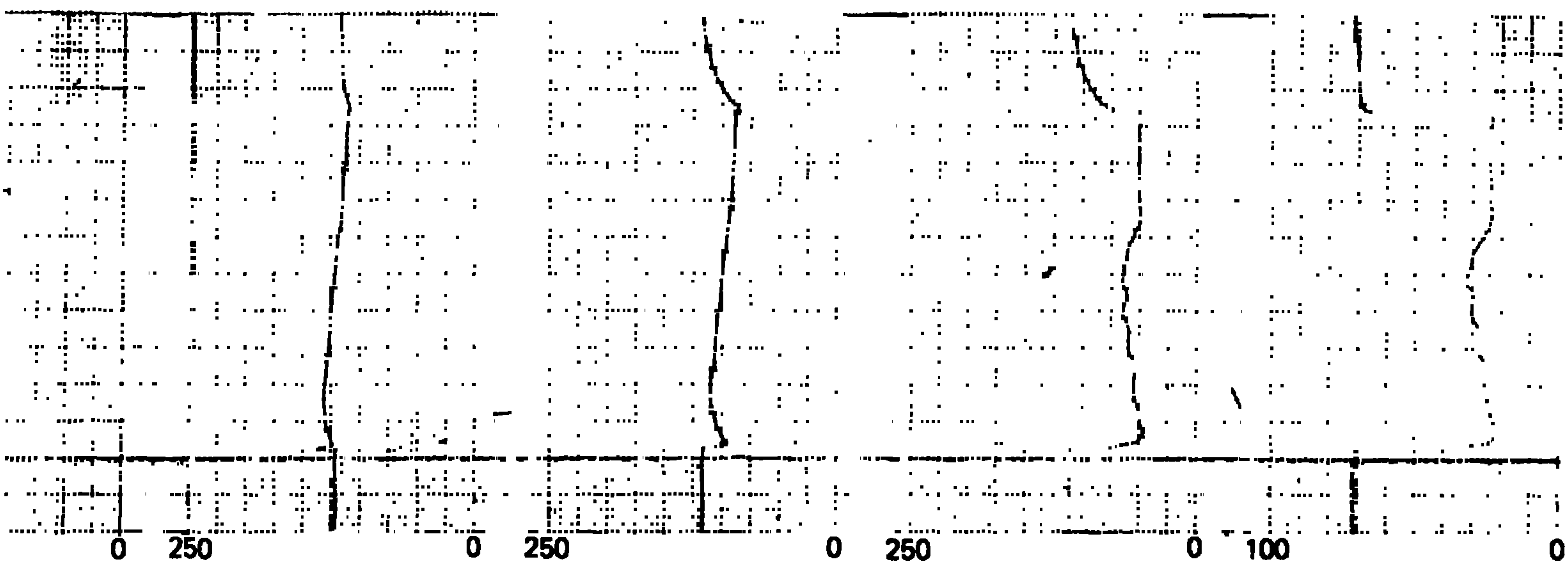
FOLDOUT FRAME



ter Body re - °F	P_1 - Pressure at Inlet to Throttle Valve - Psia	P_2 - Pressure at Outlet of Throttle Valve - Psia	P_3 - Pressure at Outlet of Heat Exchanger - Psia	P_4 - Thruster Nozzle Pressure - Psia

Data

Propellant Fill Level 50%
Vacuum Tank Wall Temperature 75°F
Storage Tank Temperature 72°F



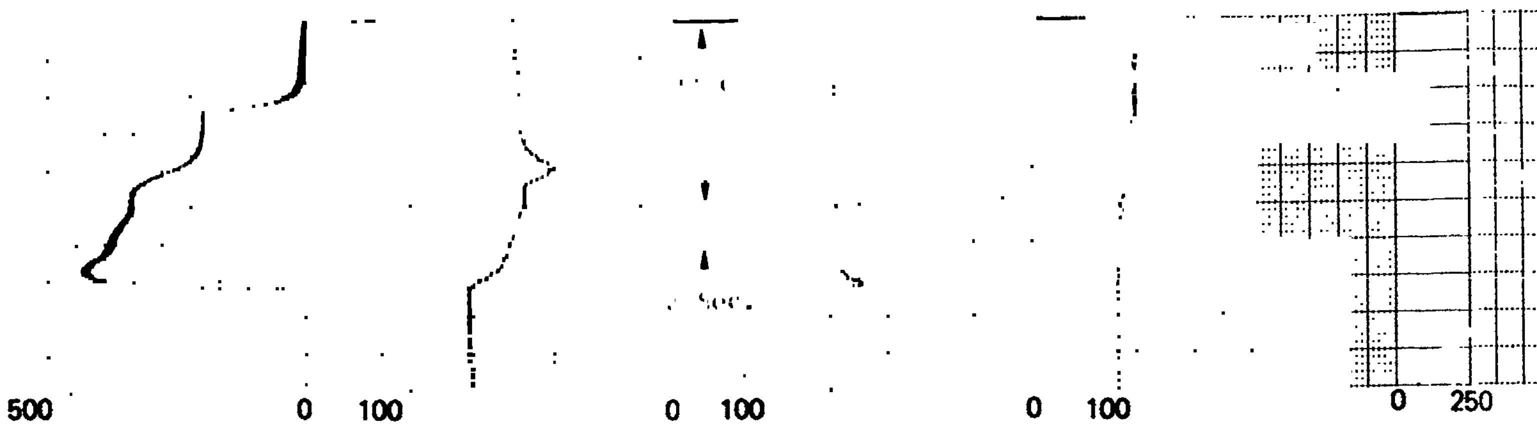
ter Body re - °F	P_1 - Pressure at Inlet to Throttle Valve - Psia	P_2 - Pressure at Outlet of Throttle Valve - Psia	P_3 - Pressure at Outlet of Heat Exchanger - Psia	P_4 - Thruster Nozzle Pressure - Psia

)ata

Propellant Fill Level 50%
Vacuum Tank Wall Temperature 75°F
Storage Tank Temperature 74°F

Figure 19-A.

FOLDOUT FRAME



Thruster Force
lb x 10^{-3}

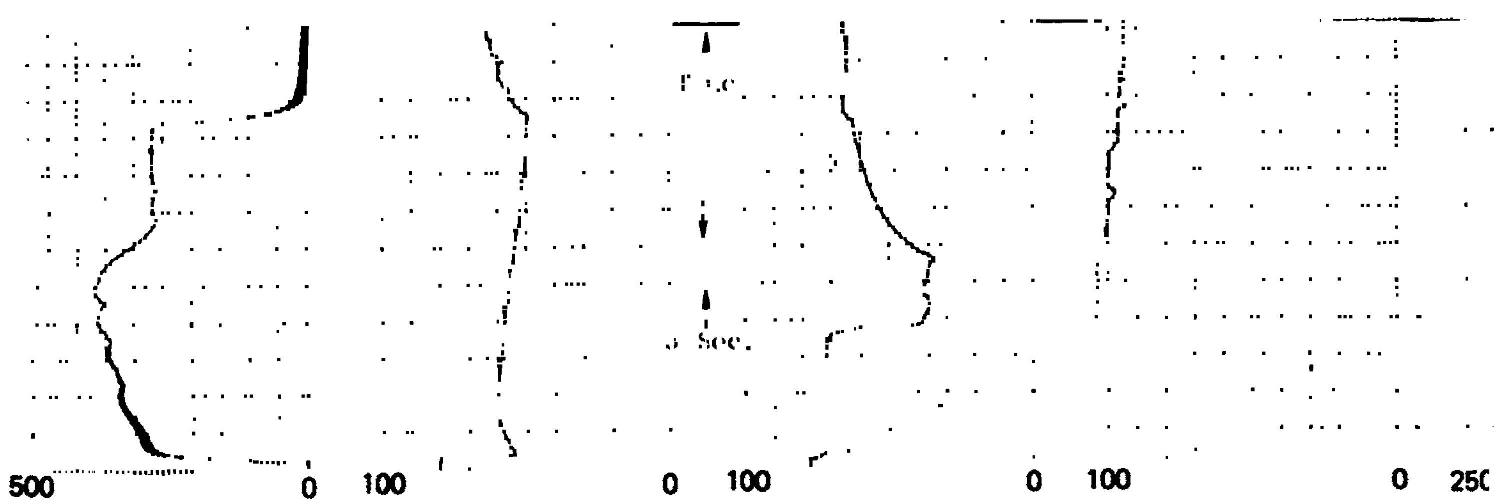
T_2 - Temperature at
Output of Throttle
Valve - ^oF

T_3 - Temperature at
Heat Exchanger
Output - ^oF

T_5 - Thruster Body
Temperature - ^oF

P_1 -
Inle
Va

Vapor Feed Pulse Data { Propellant F
Vacuum Tank
Storage Tank



Thruster Force
lb x 10^{-3}

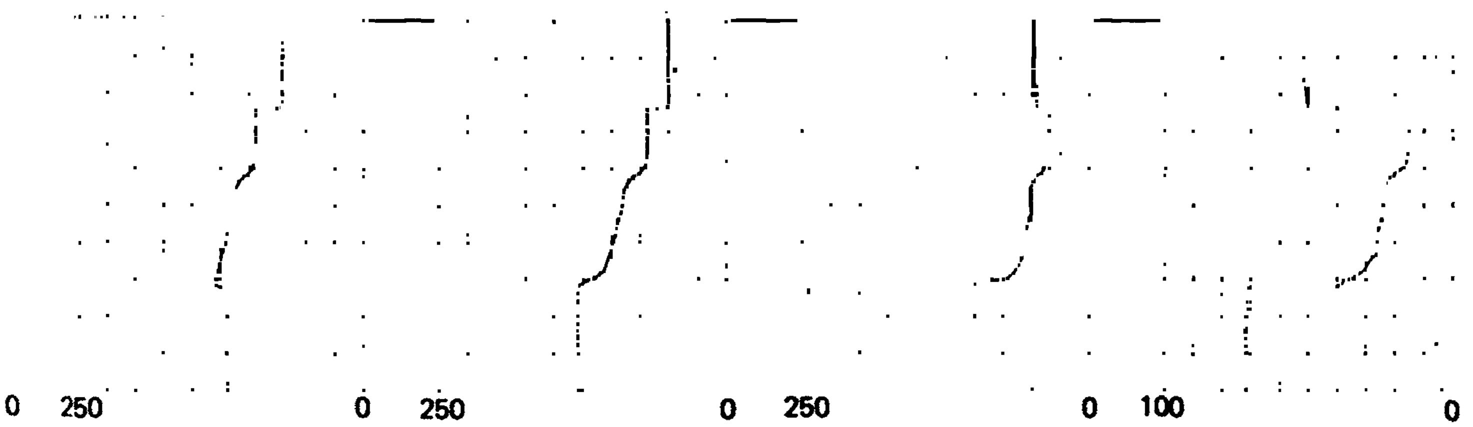
T_2 - Temperature at
Output of Throttle
Valve - ^oF

T_3 - Temperature at
Heat Exchanger
Output - ^oF

T_5 - Thruster Body
Temperature - ^oF

Liquid Feed Pulse Data { Propella
Vacuum T
Storage

Figure 19-B



·ody
°F

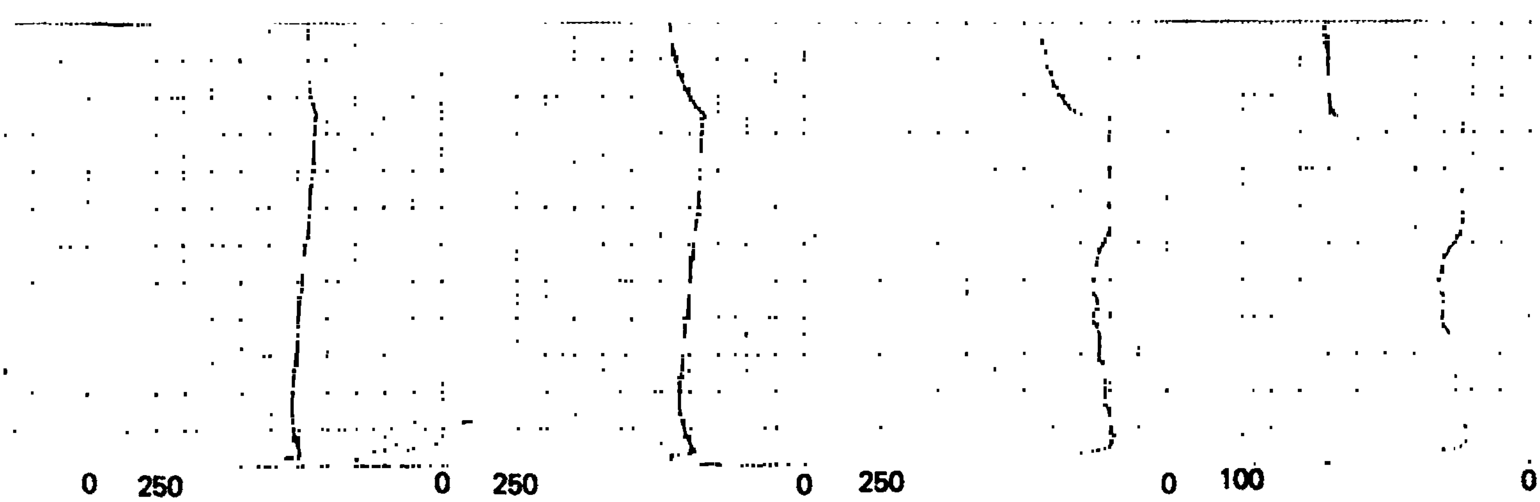
P_1 - Pressure at Inlet to Throttle Valve - Psia

P_2 - Pressure at Outlet of Throttle Valve - Psia

P_3 - Pressure at Outlet of Heat Exchanger - Psia

P_4 - Thruster Nozzle Pressure - Psia

Propellant Fill Level 50%
Vacuum Tank Wall Temperature 75°F
Storage Tank Temperature 58°F



r Body
- °F

P_1 - Pressure at Inlet to Throttle Valve - Psia

P_2 - Pressure at Outlet of Throttle Valve - Psia

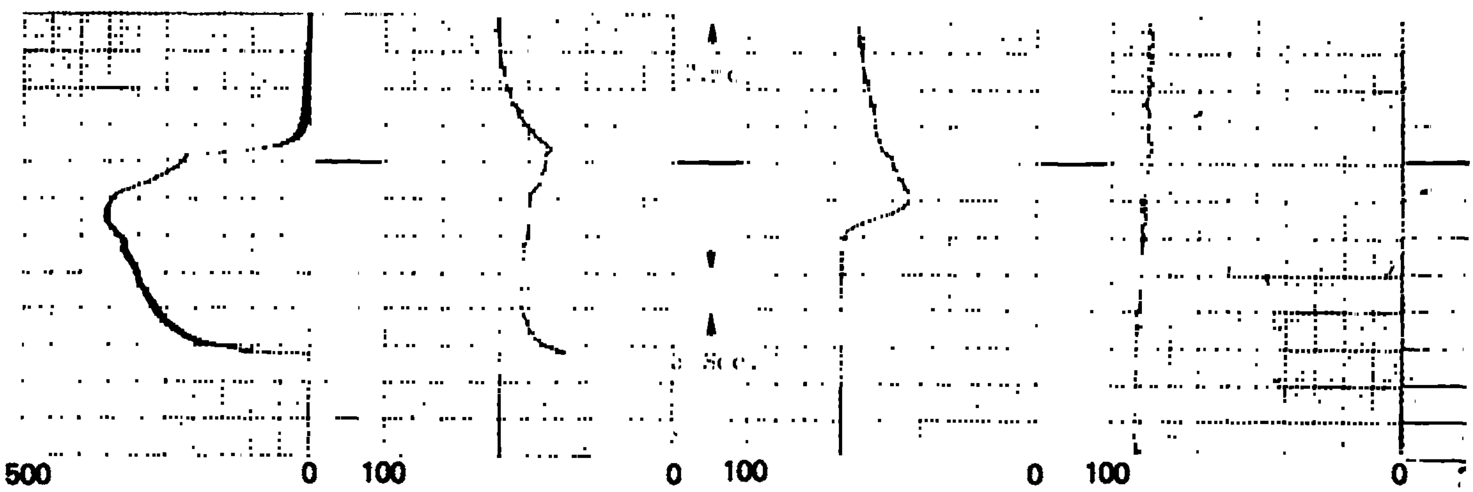
P_3 - Pressure at Outlet of Heat Exchanger - Psia

P_4 - Thruster Nozzle Pressure - Psia

Propellant Fill Level 50%
Vacuum Tank Wall Temperature 75°F
Storage Tank Temperature 60°F

Figure 19-B.

FOLDOUT FRAME



Thruster Force
lb x 10^{-3}

T_2 - Temperature at Output of Throttle Valve - ^oF

T_3 - Temperature at Heat Exchanger Output - ^oF

T_5 - Thruster Body Temperature - ^oF

Aternating Liquid-Vapor Feed Data (Starting with Liquid Feed-Switching Each 5 Seconds)

Pr
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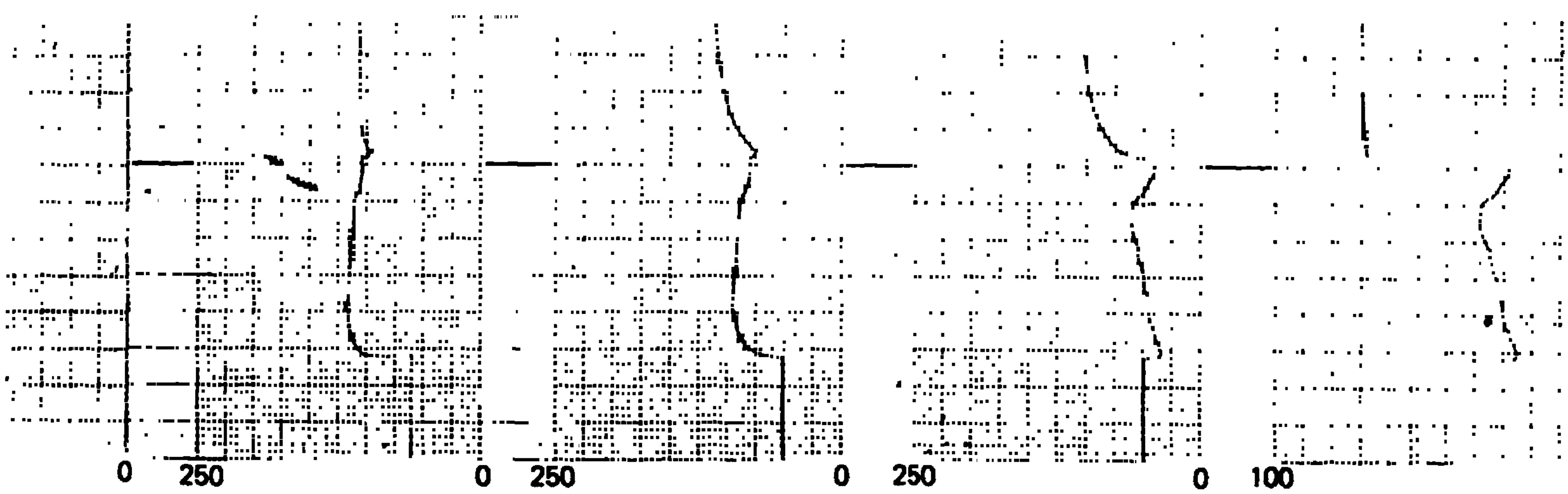
Figure 1.

FOLDOUT FRAME



ter Body
re - ^{o}F

P_1 - Pressure at Inlet to Throttle Valve - Psia

P_2 - Pressure at Outlet of Throttle Valve - Psia

P_3 - Pressure at Outlet of Heat Exchanger - Psia

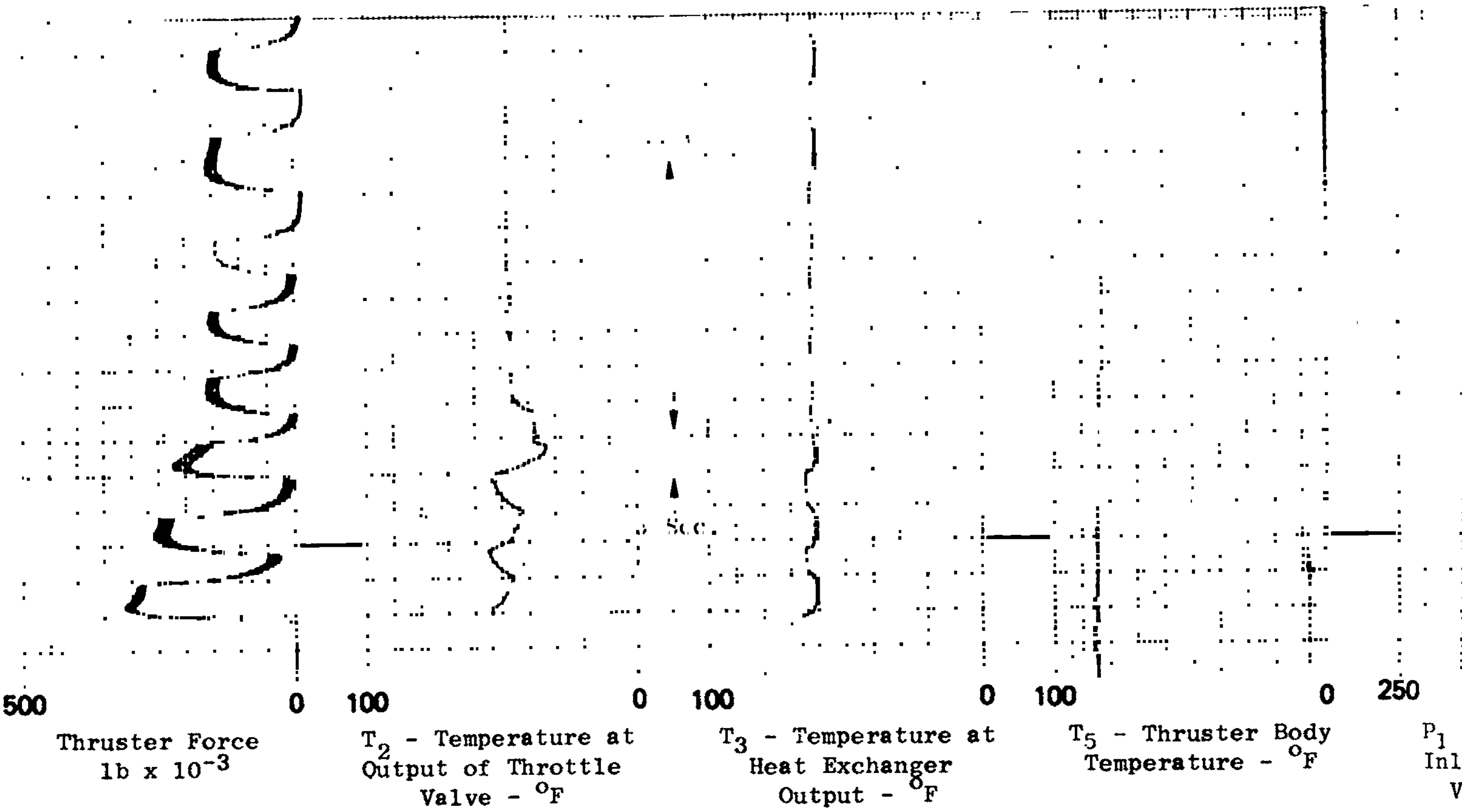
P_4 - Thruster Nozzle Pressure - Psia

ata
tching

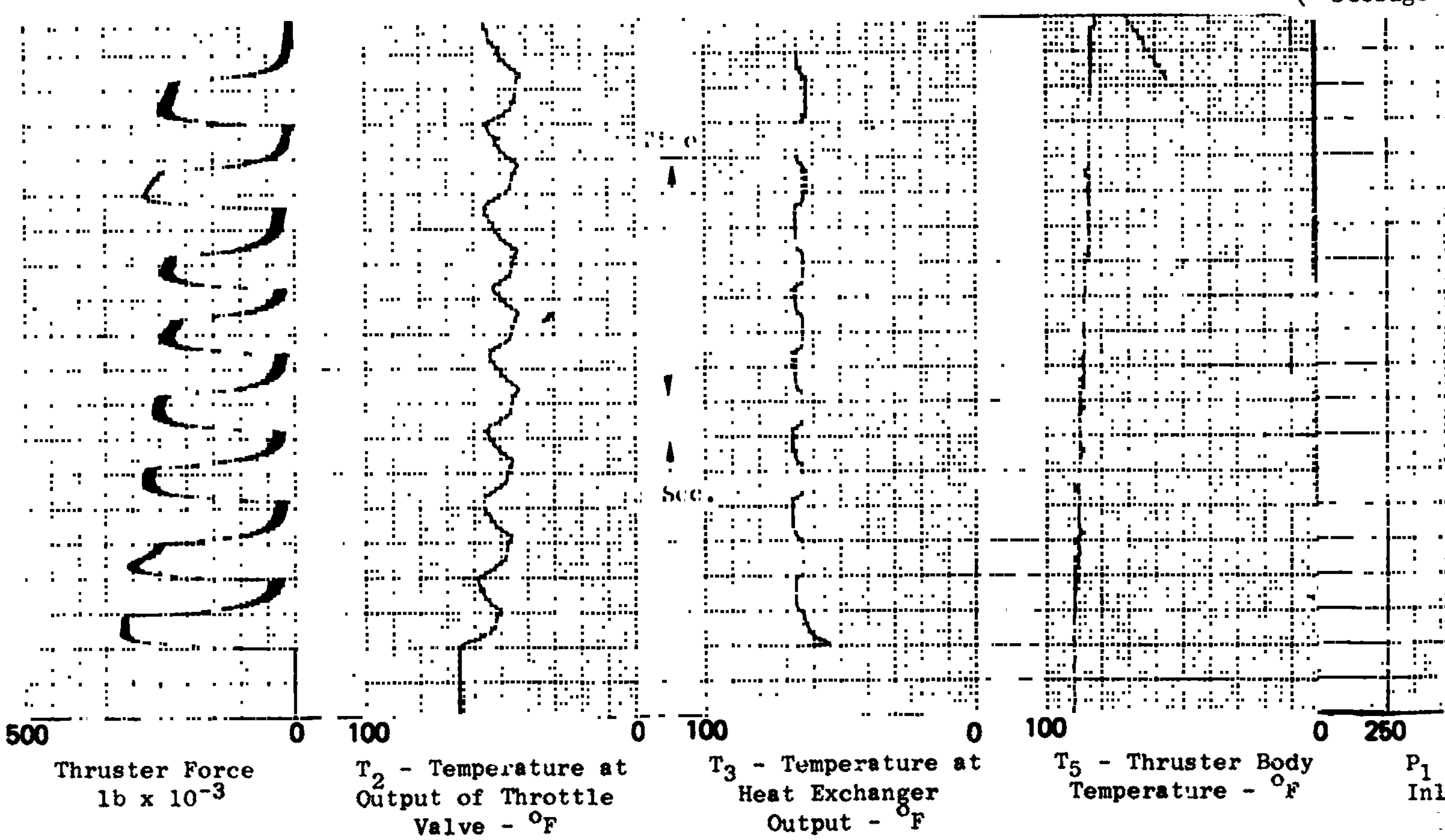
Propellant Fill Level 50%
Vacuum Tank Wall Temperature 75°F
Storage Tank Temperature 69°F

Figure 19-C.

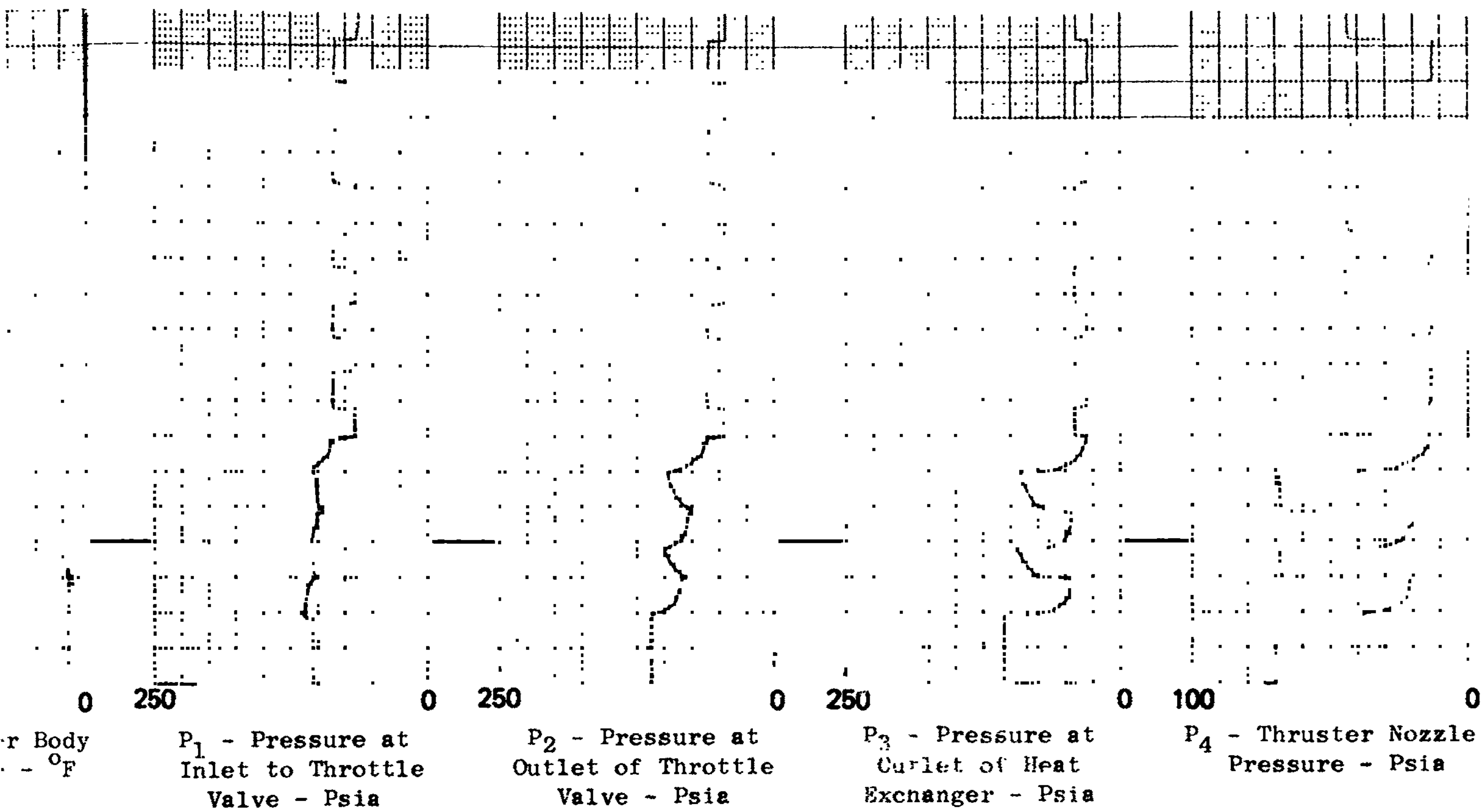
FOLDOUT F...



Vapor Feed Pulse Data { Propella
Vacuum T
Storage

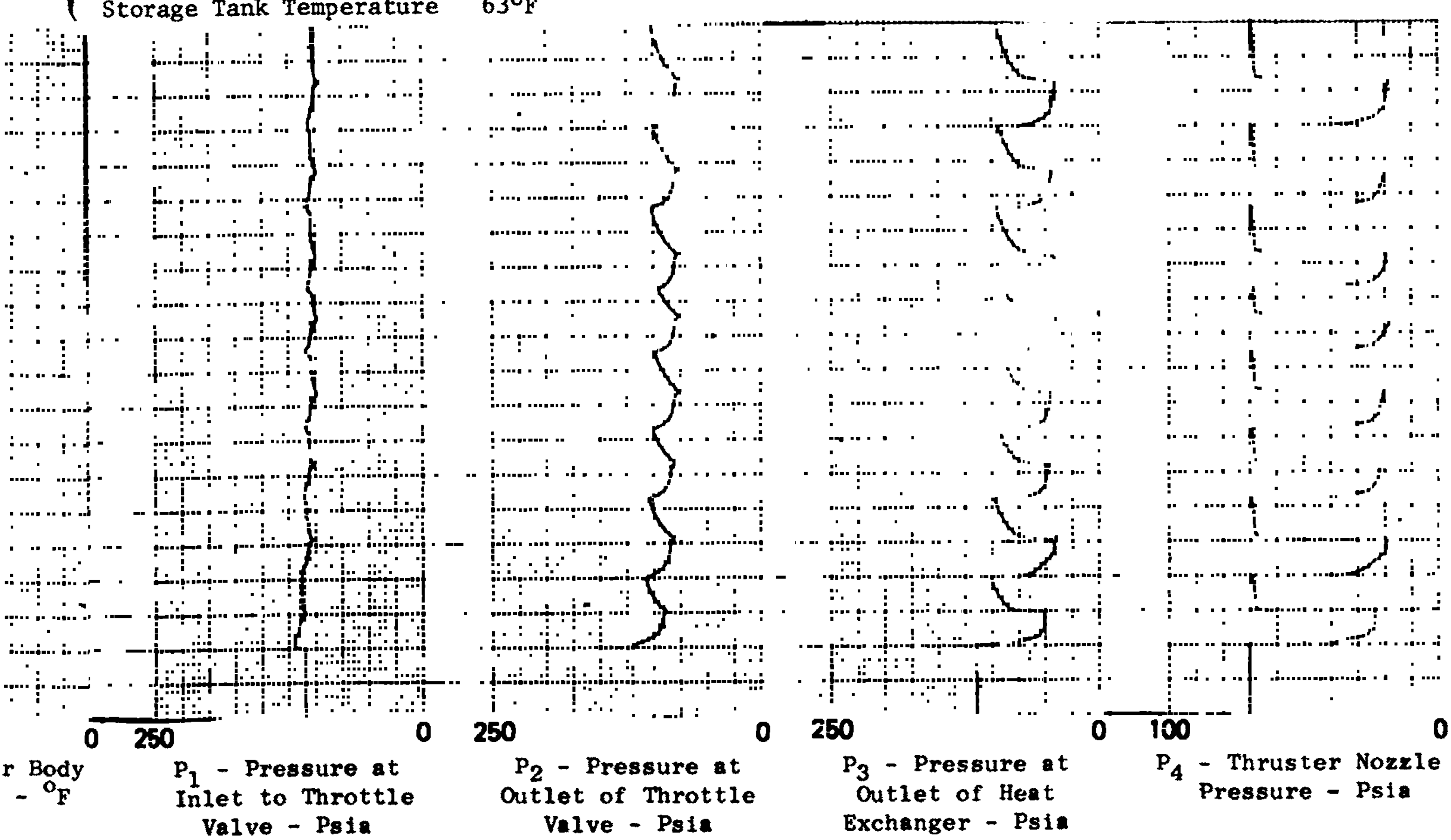


Liquid Feed Pulse Data { Propellant
Vacuum Tan
Storage Ta

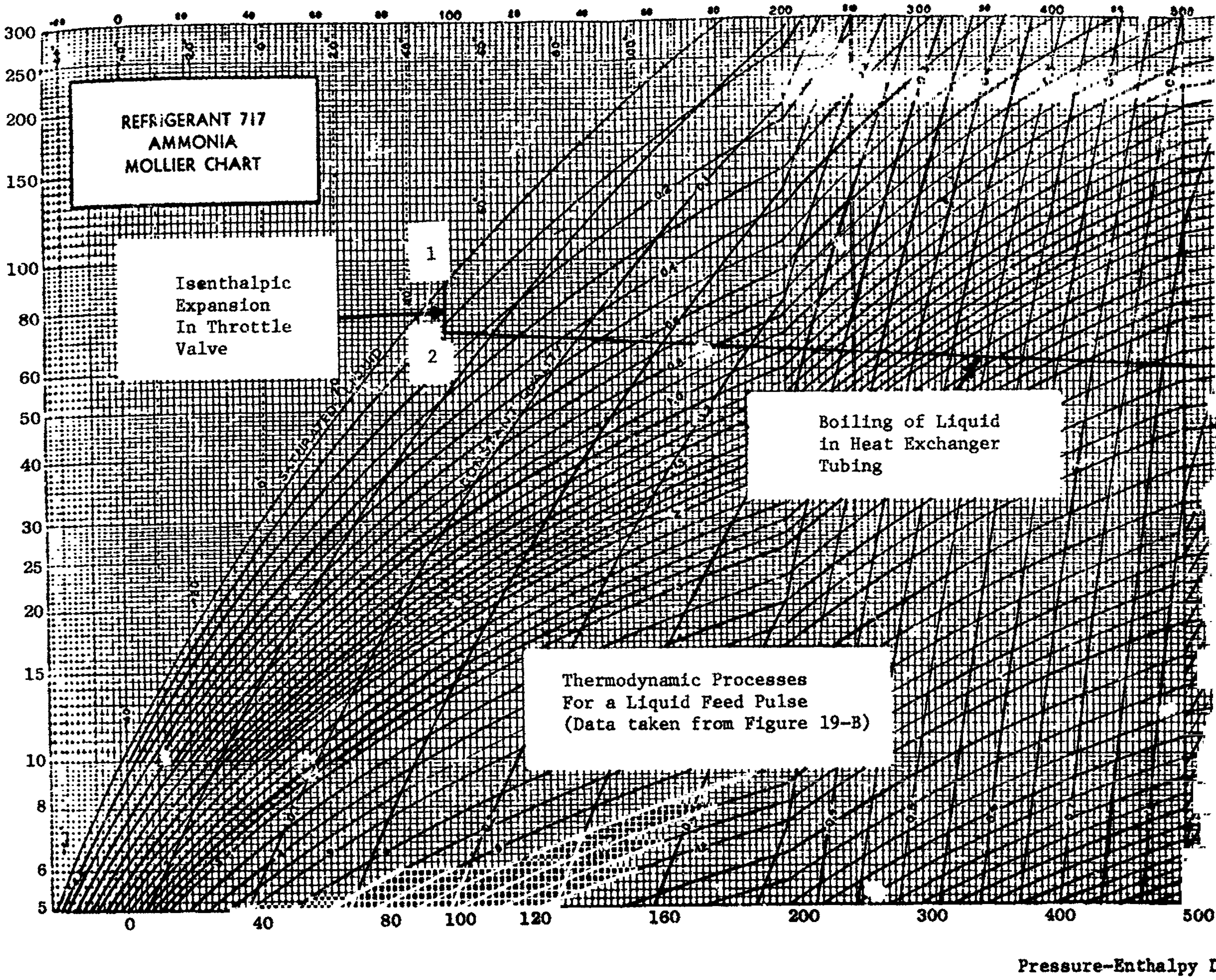


ta

Propellant Fill Level 50%
Vacuum Tank Wall Temperature 75°F
Storage Tank Temperature 63°F

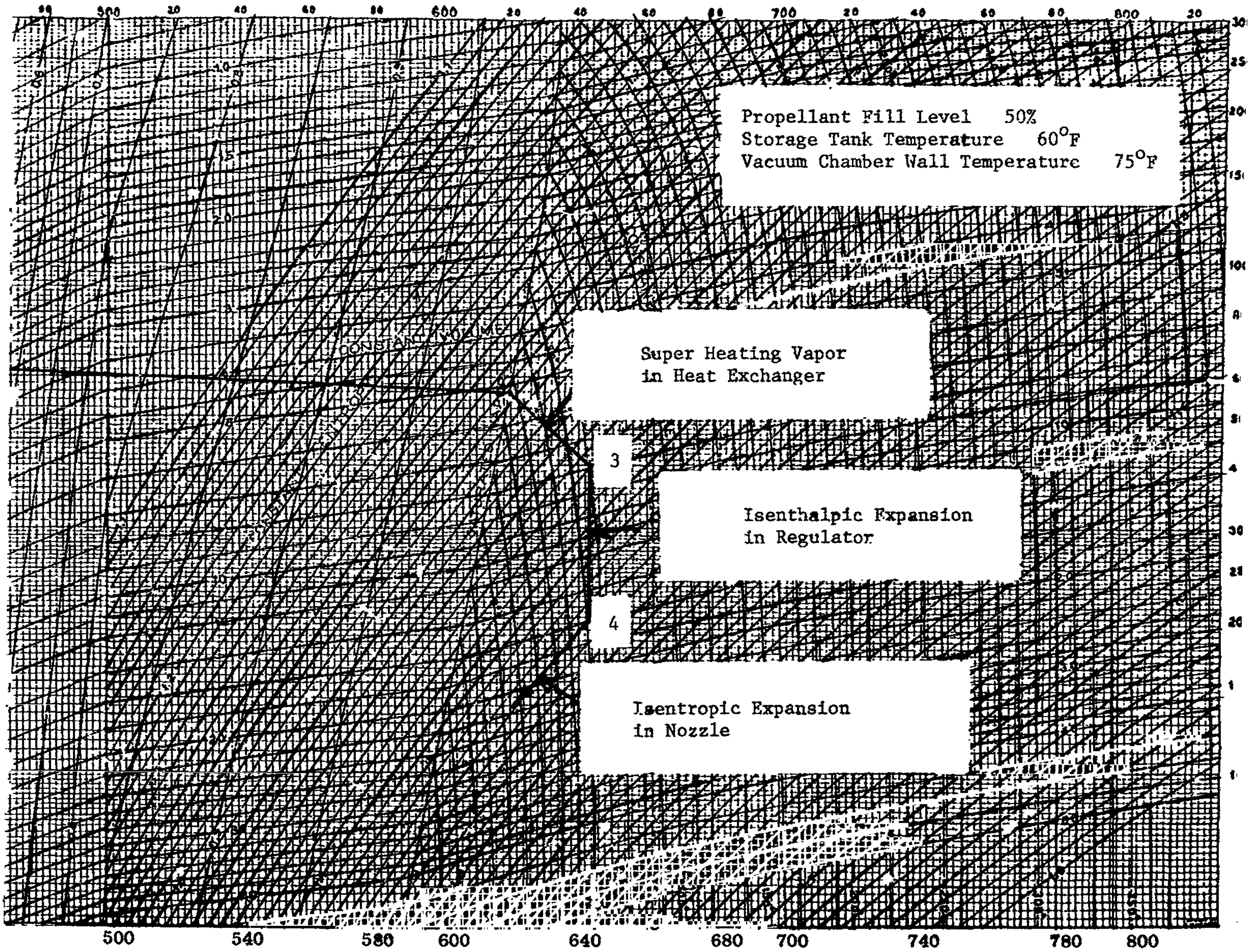


Propellant Fill Level 50%
Vacuum Tank Wall Temperature 75°F
Storage Tank Temperature 66°F



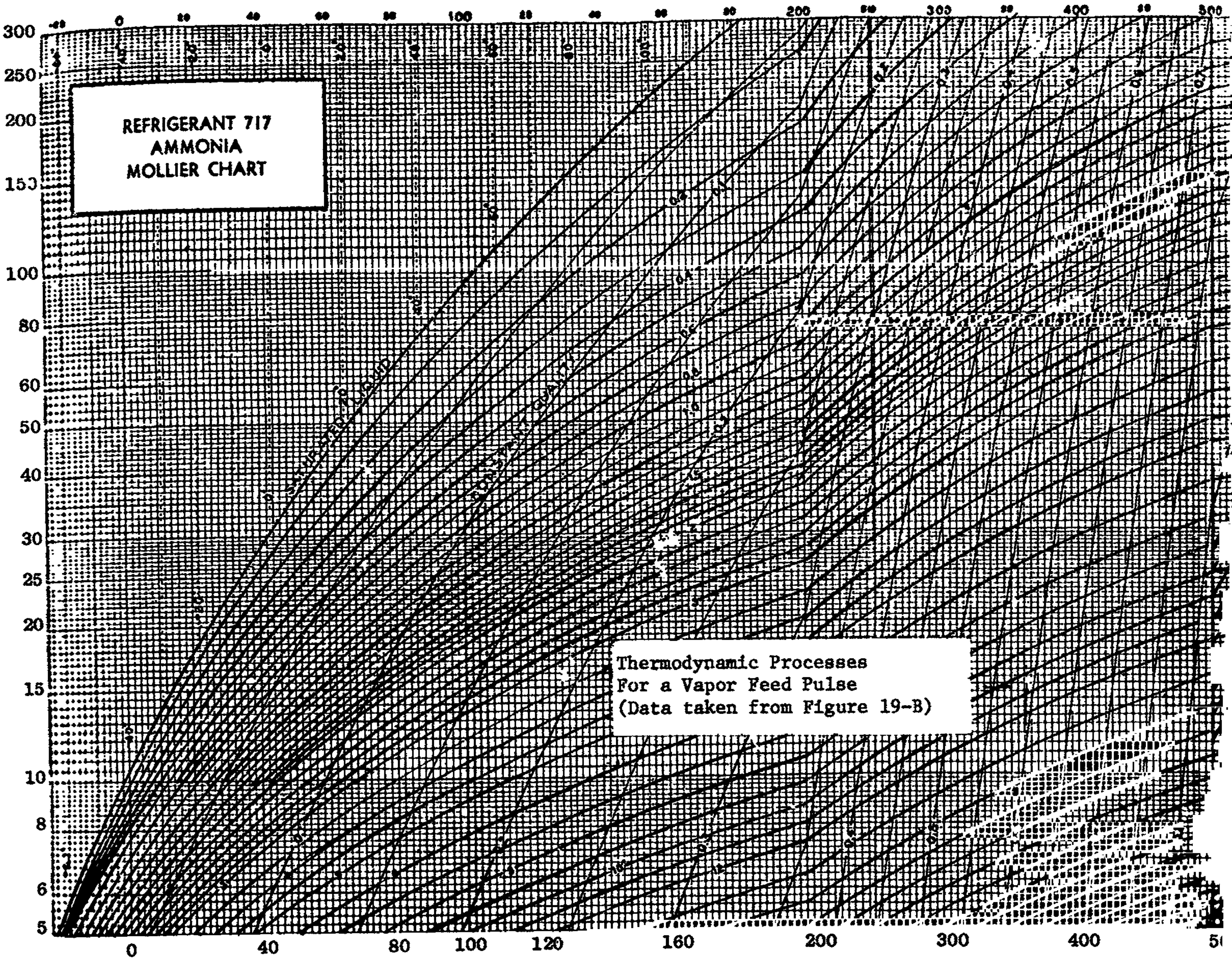
Pressure-Enthalpy I

Figure 19-E.



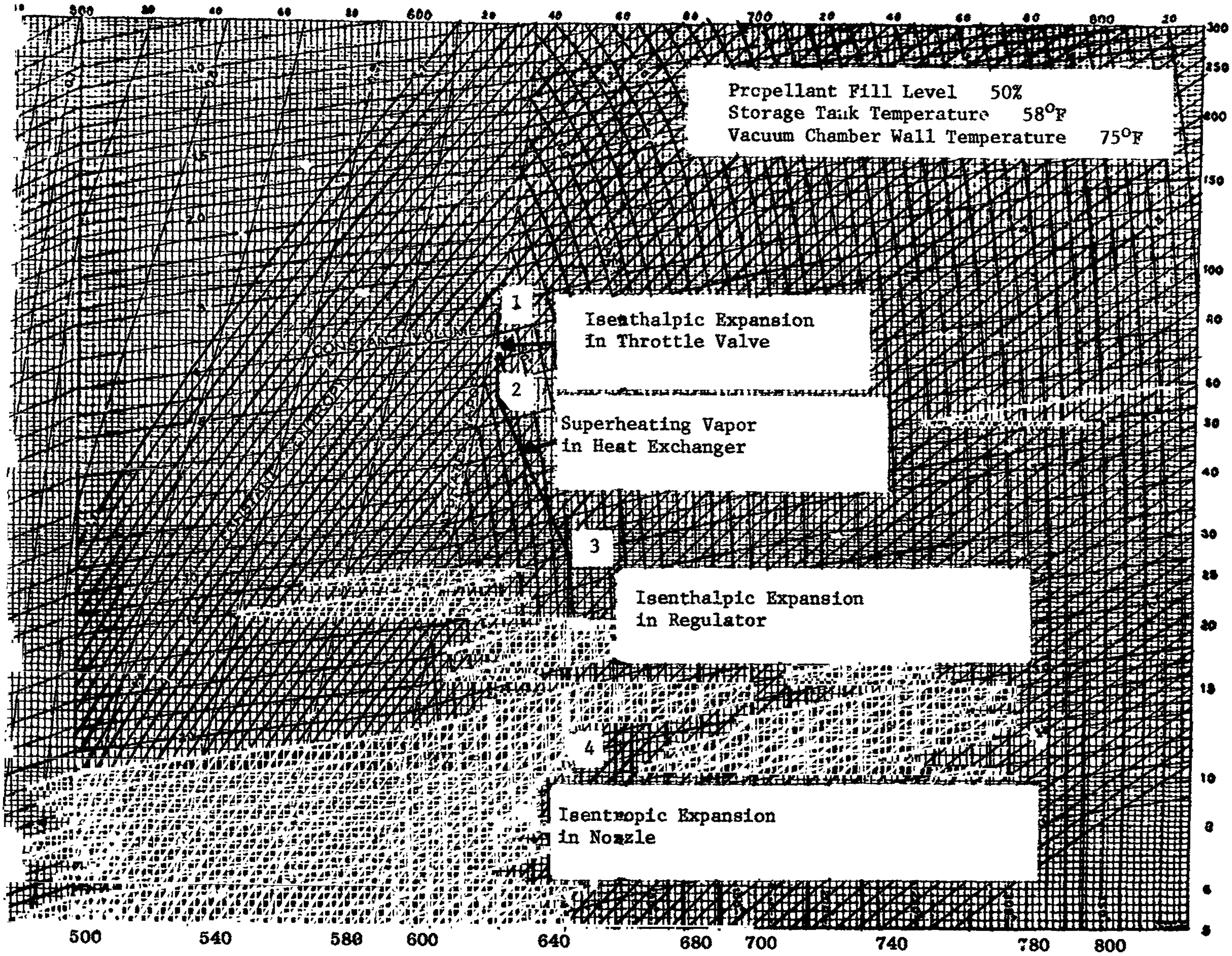
re-Enthalpy Diagram   Heat Content - Btu, Per Lb.

Figure 19-E.



Pressure-Enthalpy D

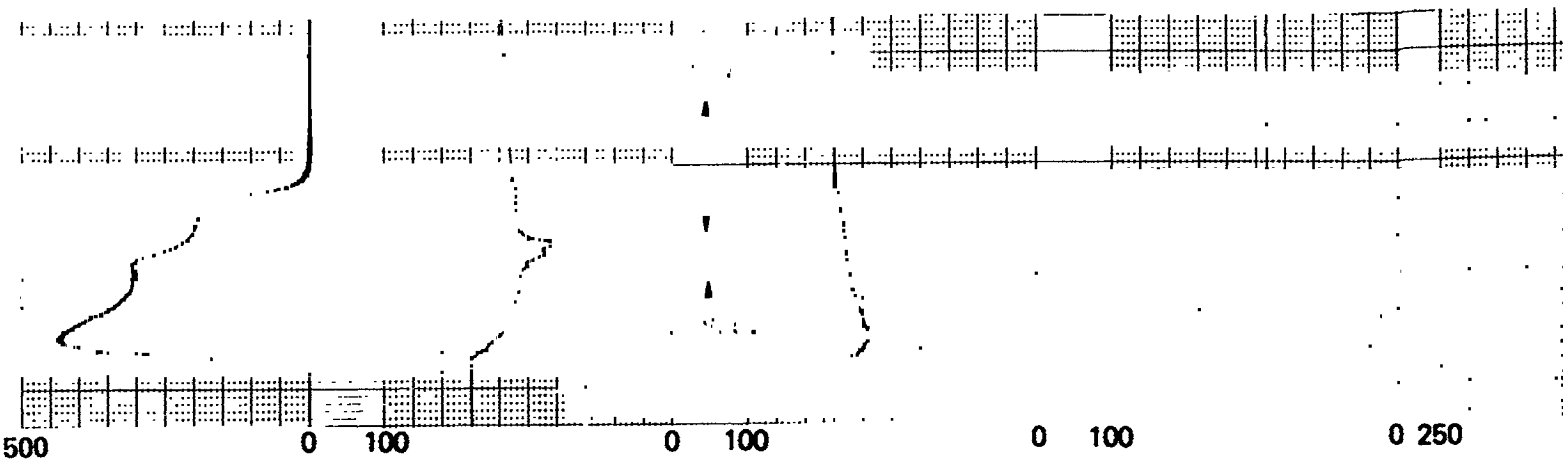
Figure 19-F.



ıthalpy Diagram

re 19-F.

FOLDOUT FRAME



Thruster Force
lb x 10^{-3}

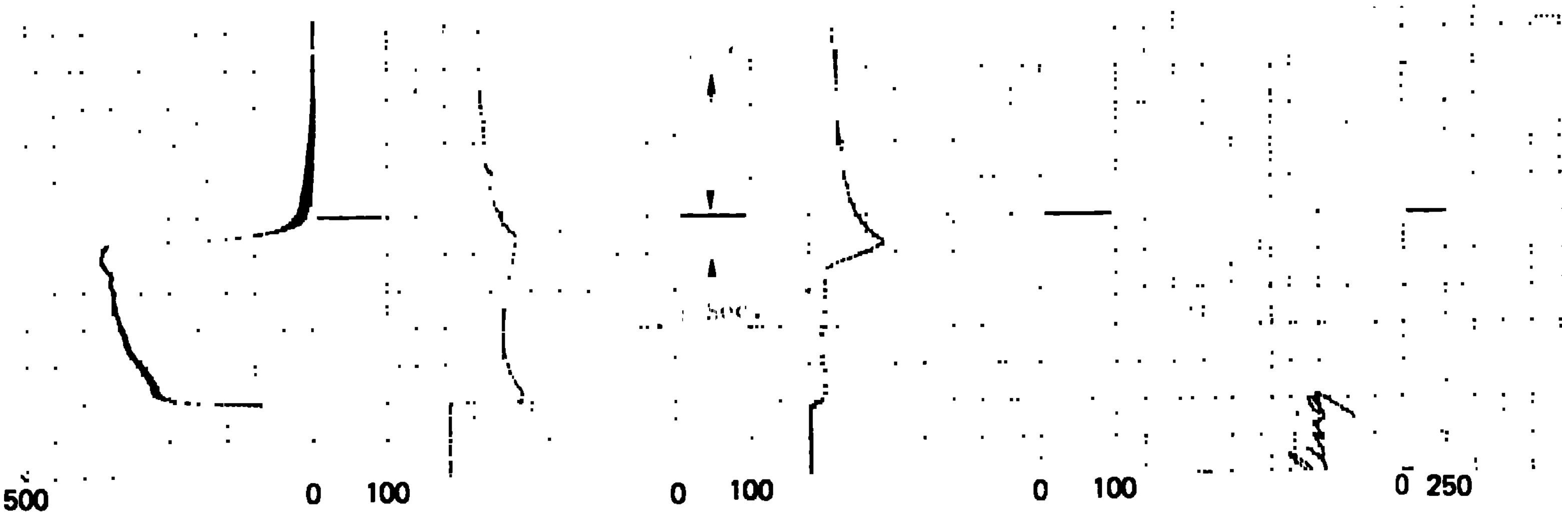
T_2 - Temperature at Output of Throttle Valve - ^{o}F

T_3 - Temperature at Heat Exchanger Output - ^{o}F

T_5 - Thruster Body Temperature - ^{o}F

P_1 - Pr
Inlet t
Valve

Vapor Feed Pulse Data { Propellant Fil
Vacuum Tank Wa
Storage Tank T



Thruster Force
lb x 10^{-3}

T_2 - Temperature at Output of Throttle Valve - ^{o}F

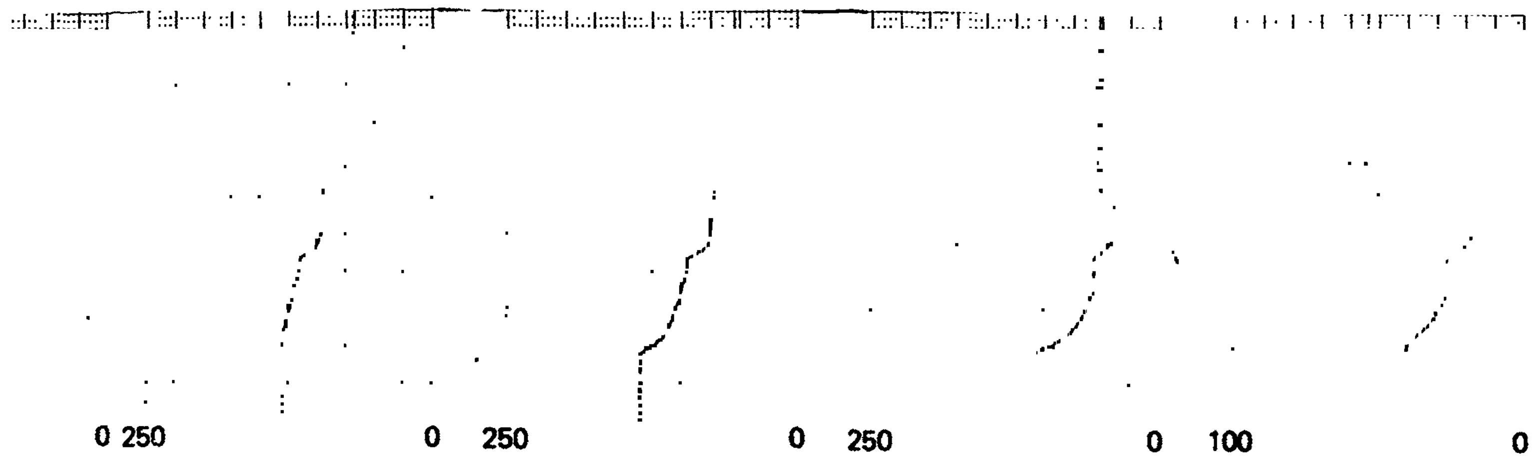
T_3 - Temperature at Heat Exchanger Output - ^{o}F

T_5 - Thruster Body Temperature - ^{o}F

P_1 -
Inlet
Val

Liquid Feed Pulse Data { Propellant Fil
Vacuum Tank Wa
Storage Tank T

Figure 20-A



er Body
e - ^{o}F

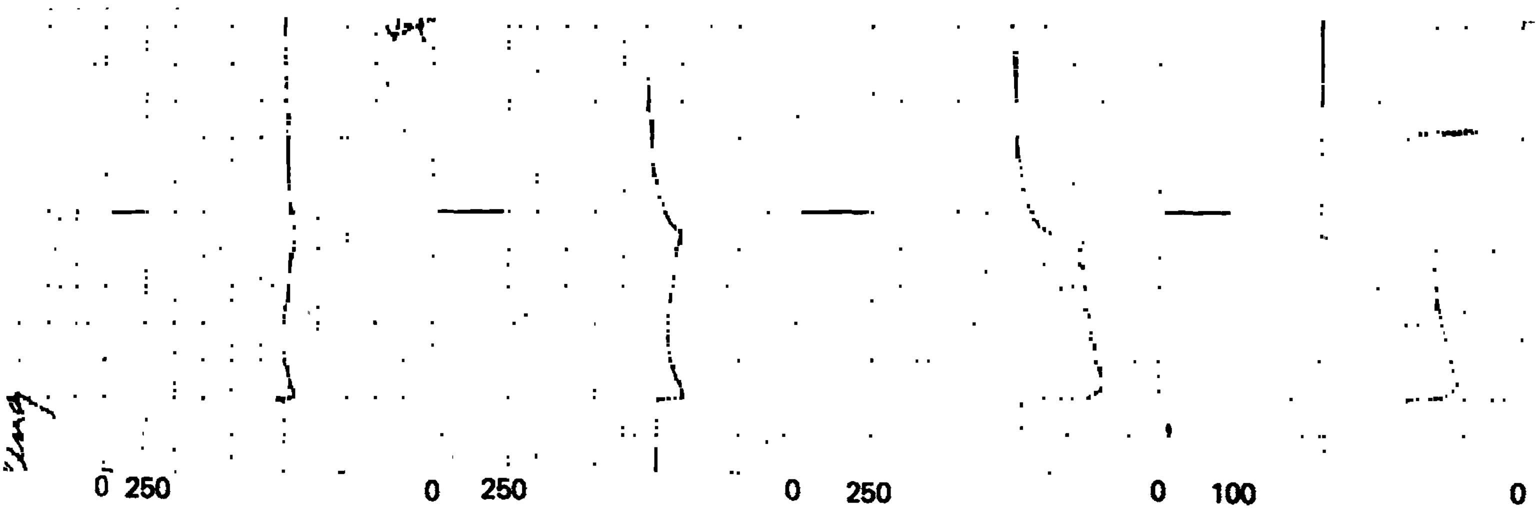
P_1 - Pressure at Inlet to Throttle Valve - Psia

P_2 - Pressure at Outlet of Throttle Valve - Psia

P_3 - Pressure at Outlet of Heat Exchanger - Psia

P_4 - Thruster Nozzle Pressure - Psia

Propellant Fill Level 25%
Vacuum Tank Wall Temperature 75°F
Storage Tank Temperature 70°F



'er Body
'e - ^{o}F

P_1 - Pressure at Inlet to Throttle Valve - Psia

P_2 - Pressure at Outlet of Throttle Valve - Psia

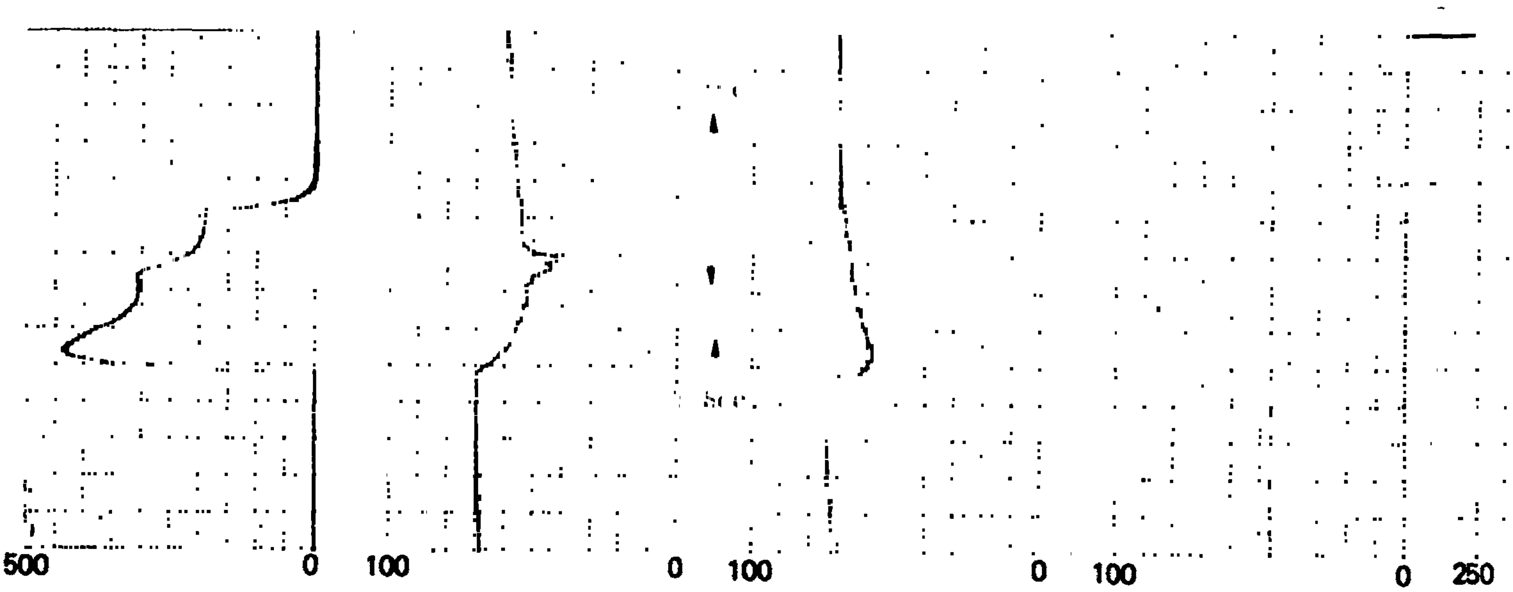
P_3 - Pressure at Outlet of Heat Exchanger - Psia

P_4 - Thruster Nozzle Pressure - Psia

Propellant Fill Level 25%
Vacuum Tank Wall Temperature 75°F
Storage Tank Temperature 71°F

Figure 20-A.

FOLDOUT FRAME



Thruster Force
lb x 10^{-3}

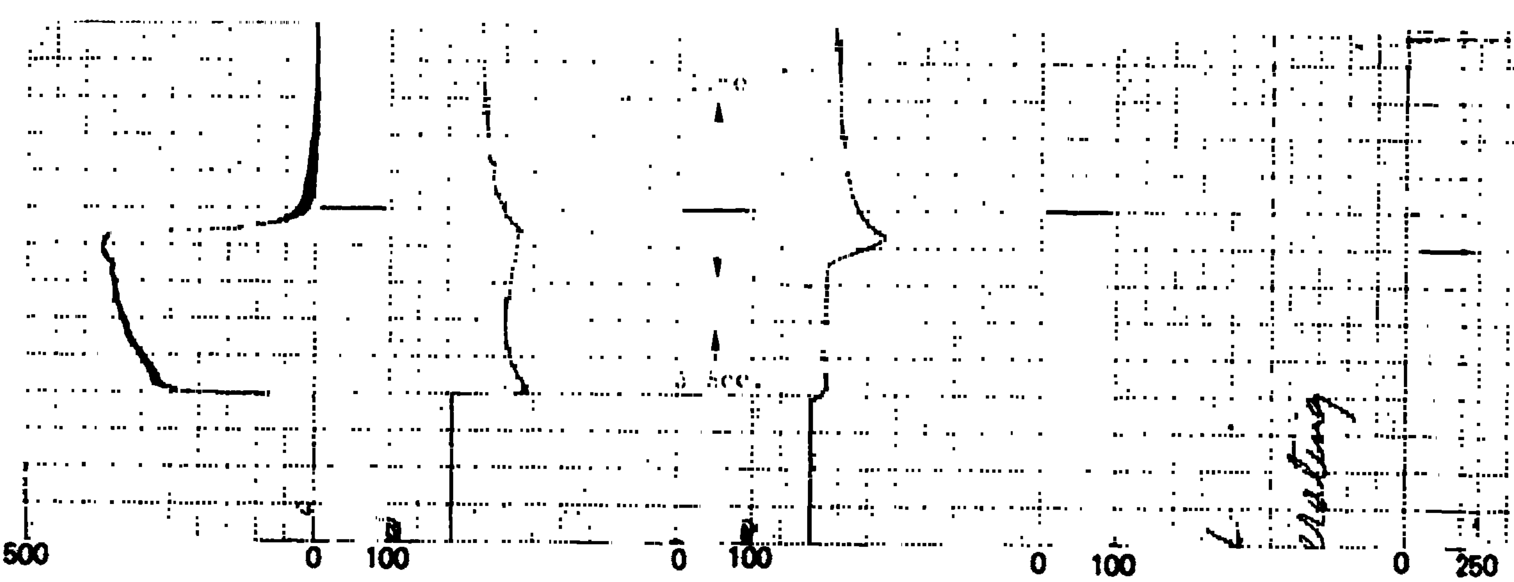
T_2 - Temperature at Output of Throttle Valve - ^oF

T_3 - Temperature at Heat Exchanger Output - ^oF

T_5 - Thruster Body Temperature - ^oF

F
I

Vapor Feed Pulse Data { Propellant
Vacuum Tank
Storage Tan



Thruster Force
lb x 10^{-3}

T_2 - Temperature at Output of Throttle Valve - ^oF

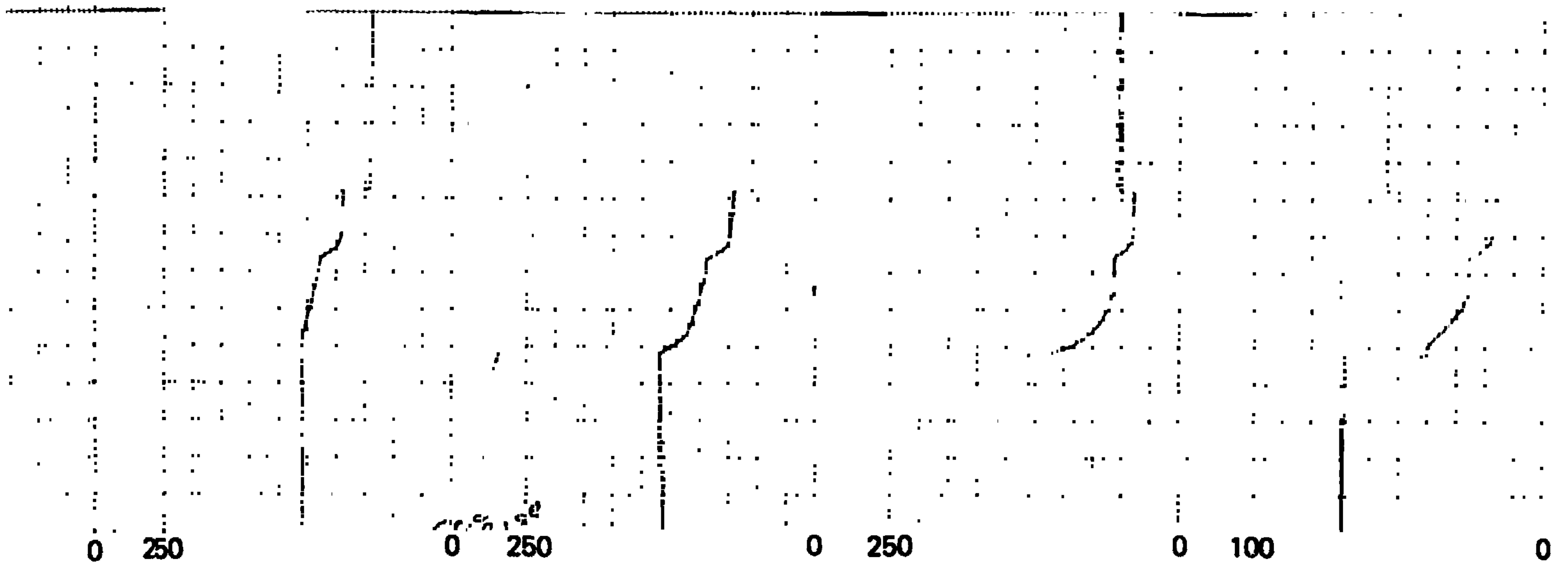
T_3 - Temperature at Heat Exchanger Output - ^oF

T_5 - Thruster Body Temperature - ^oF

P
I

Liquid Feed Pulse Data { Propellan
Vacuum Ta
Storage T

Figure 20-



· Body
- °F

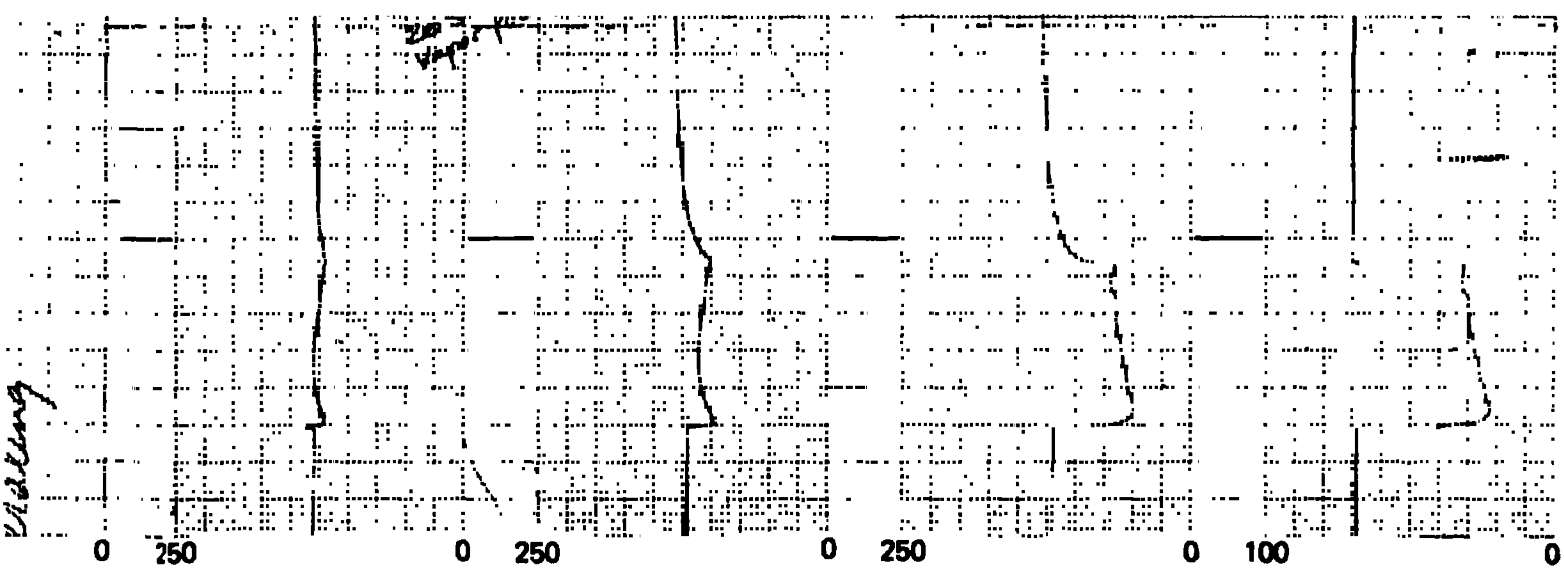
P_1 - Pressure at Inlet to Throttle Valve - Psia

P_2 - Pressure at Outlet of Throttle Valve - Psia

P_3 - Pressure at Outlet of Heat Exchanger - Psia

P_4 - Thruster Nozzle Pressure - Psia

Propellant Fill Level 25%
Vacuum Tank Wall Temperature 75°F
Storage Tank Temperature 56°F



er Body
e - °F

P_1 - Pressure at Inlet to Throttle Valve - Psia

P_2 - Pressure at Outlet of Throttle Valve - Psia

P_3 - Pressure at Outlet of Heat Exchanger - Psia

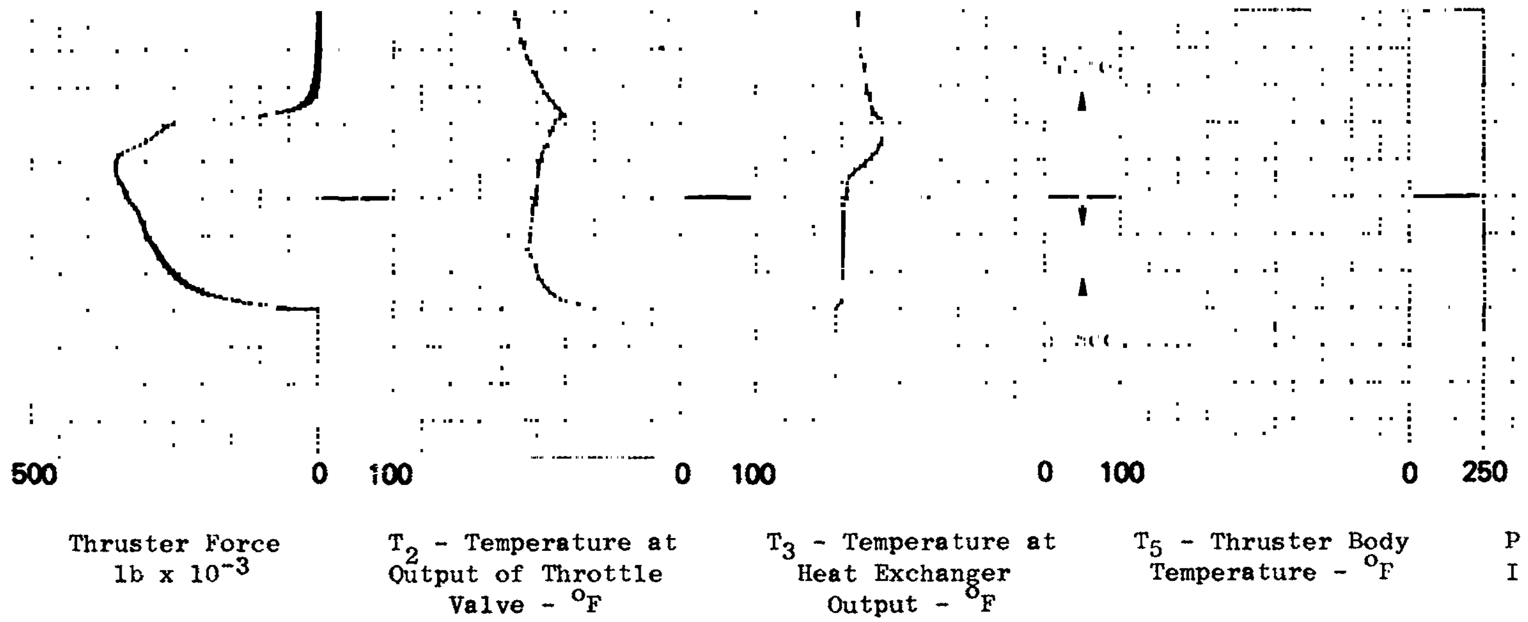
P_4 - Thruster Nozzle Pressure - Psia

Propellant Fill Level 25%
Vacuum Tank Wall Temperature 75°F
Storage Tank Temperature 58°F

Figure 20-B.

FOLD... FRAME

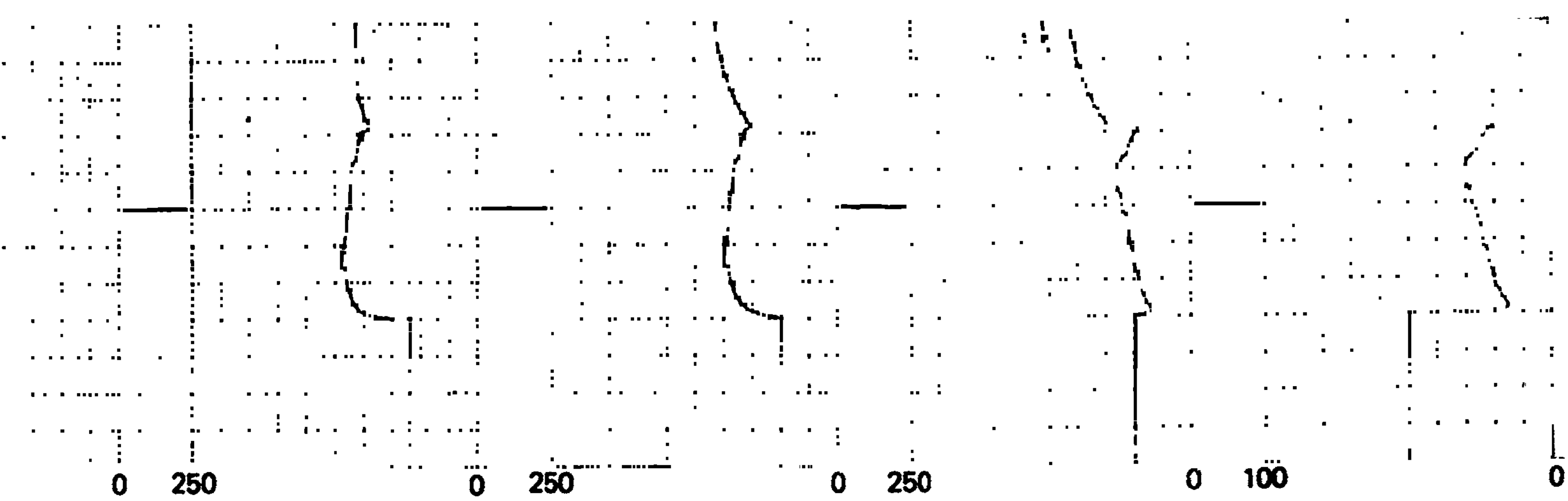
FOLDOUT FRAME



Alternating Liquid-Vapor Feed Data (Starting With Liquid Feed-Switching Each 5 Seconds) { Propel Vacuum Storag

Figure 20-C.

FOLDOUT FRAME



ter Body
re - ^{o}F

P_1 - Pressure at
Inlet to Throttle
Valve - Psia

P_2 - Pressure at
Outlet of Throttle
Valve - Psia

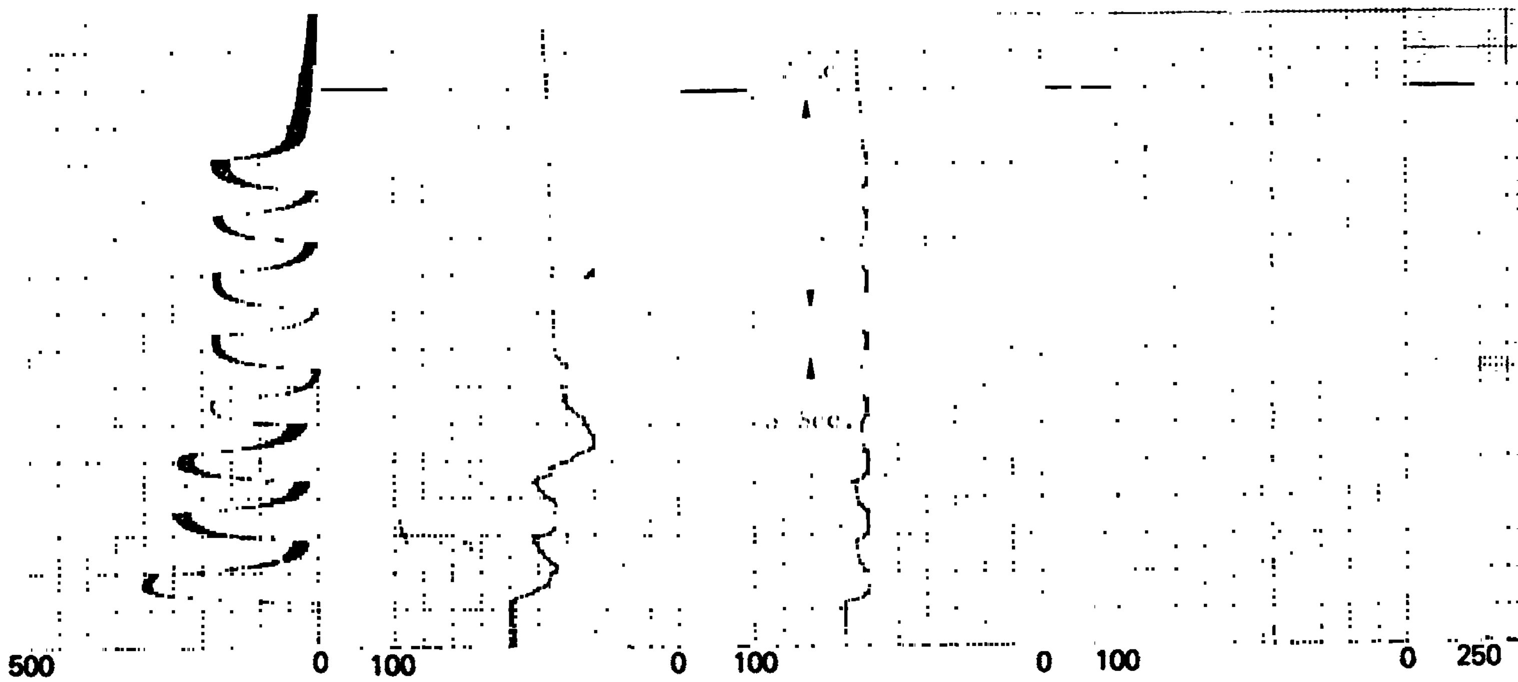
P_3 - Pressure at
Outlet of Heat
Exchanger - Psia

P_4 - Thruster Nozzle
Pressure - Psia

ata
ching

Propellant Fill Level 25%
Vacuum Tank Wall Temperature 75^{o}F
Storage Tank Temperature 70^{o}F

Figure 20-C.



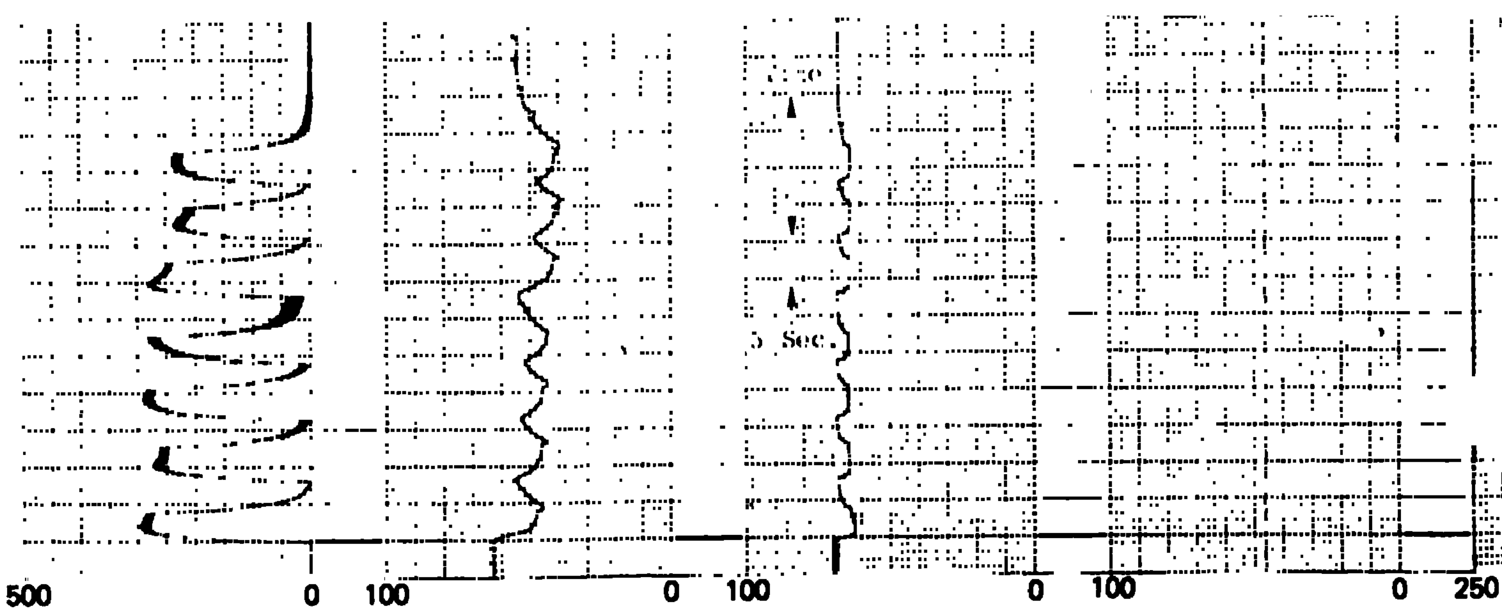
Thruster Force
lb x 10^{-3}

T_2 - Temperature at Output of Throttle Valve - ^oF

T_3 - Temperature at Heat Exchanger Output - ^oF

T_5 - Thruster Body Temperature - ^oF

Vapor Feed Pulse Data { Propella
Vacuum T
Storage



Thruster Force
lb x 10^{-3}

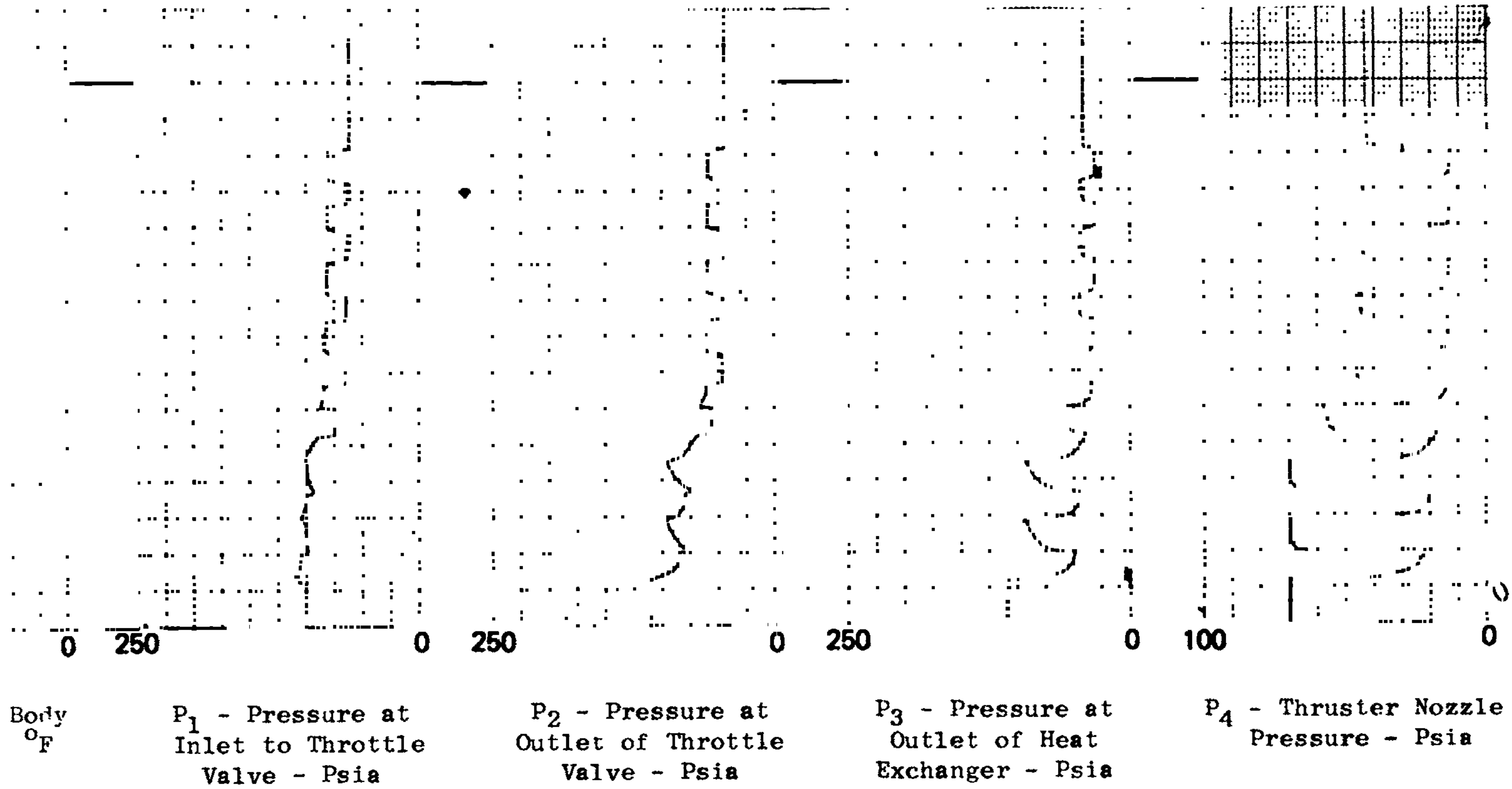
T_2 - Temperature at Output of Throttle Valve - ^oF

T_3 - Temperature at Heat Exchanger Output - ^oF

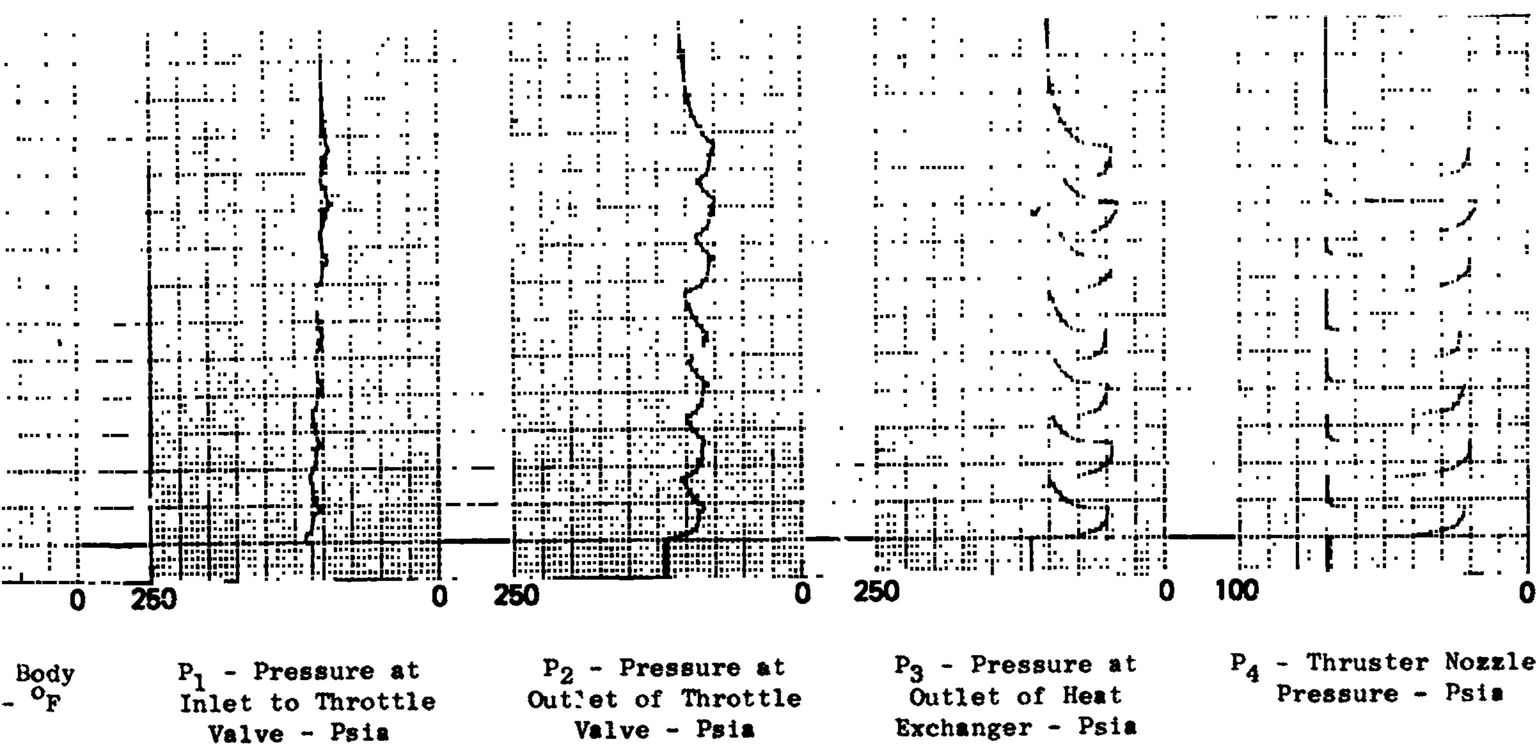
T_5 - Thruster Body Temperature - ^oF

Liquid Feed Pulse Data { Propell
Vacuum
Storage

Figure 2



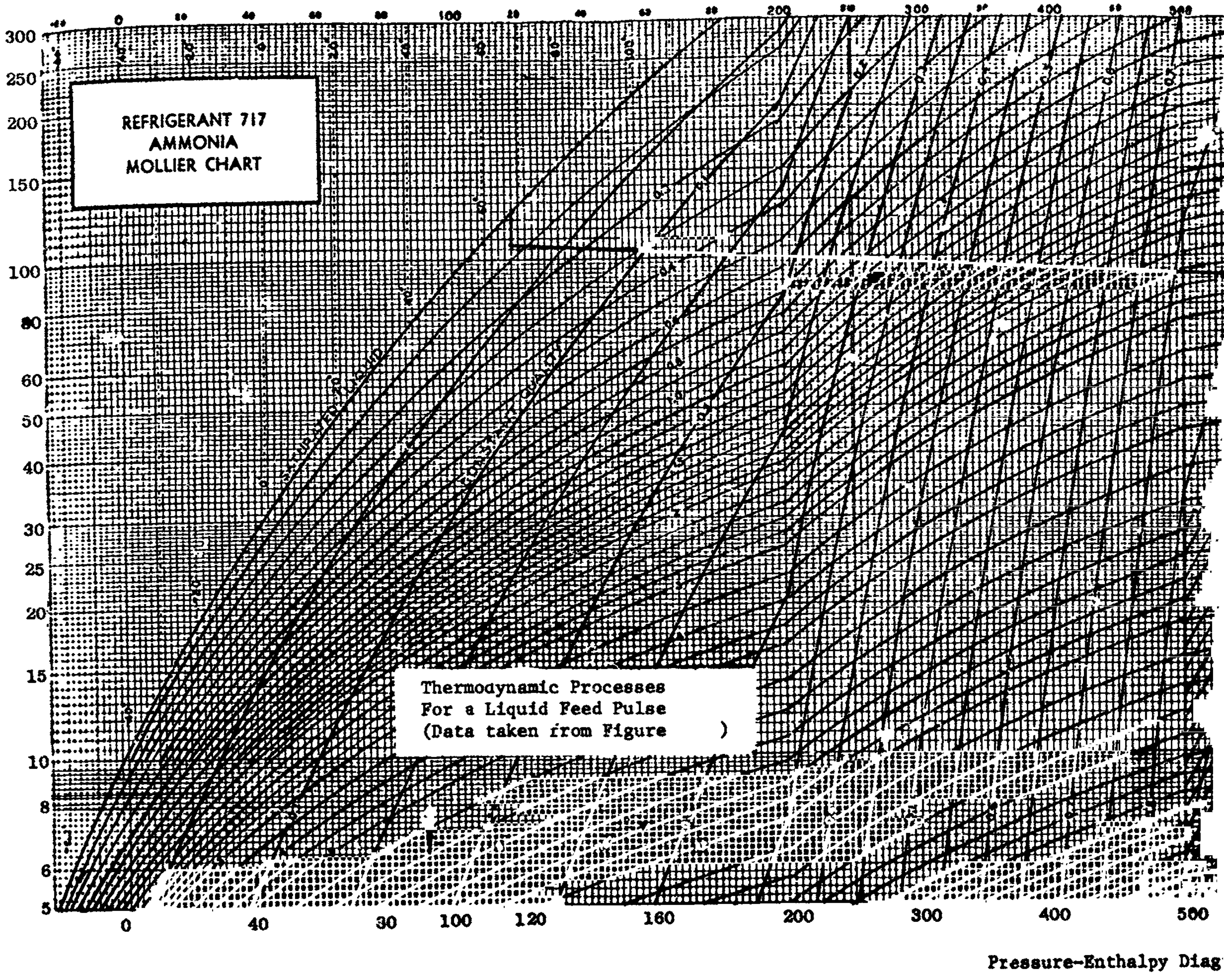
Propellant Fill Level 25%
Vacuum Tank Wall Temperature 75°F
Storage Tank Temperature 62°F



Propellant Fill Level 25%
Vacuum Tank Wall Temperature 75°F
Storage Tank Temperature 66°F

Figure 20-D. FOLDOUT FRAME

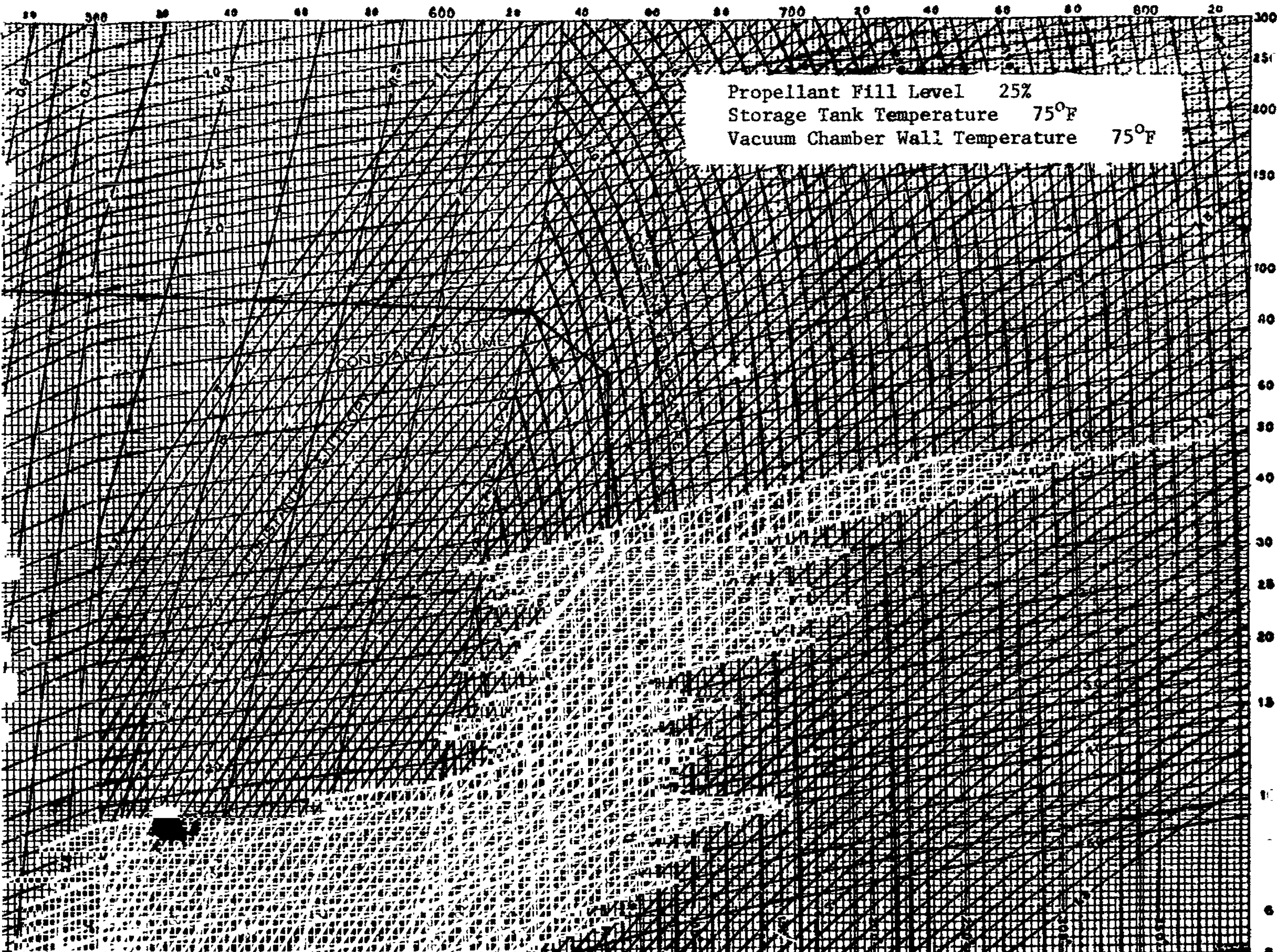
FRAME



Pressure-Enthalpy Diag

Figure 20-E

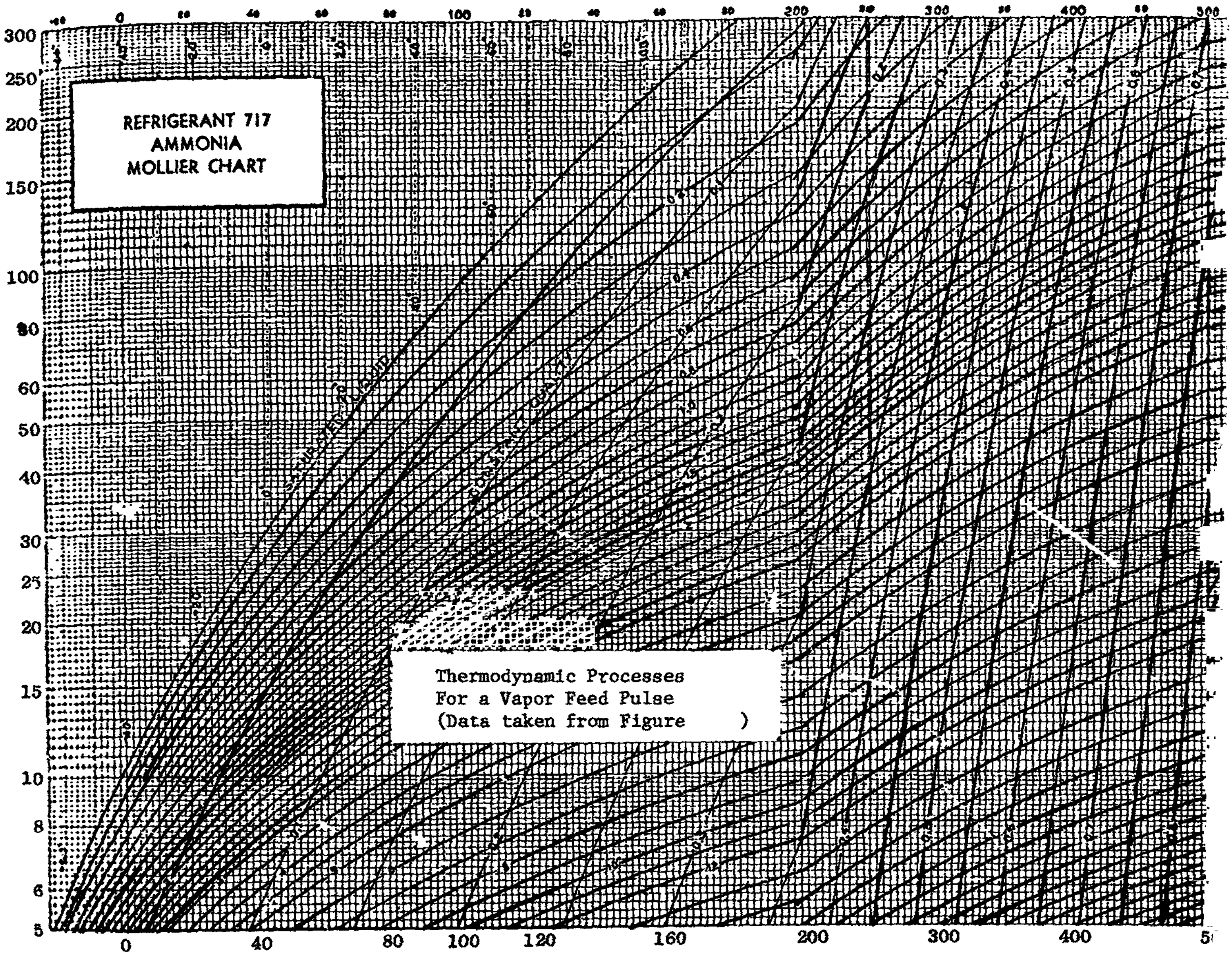
FRAME



Enthalpy Diagram

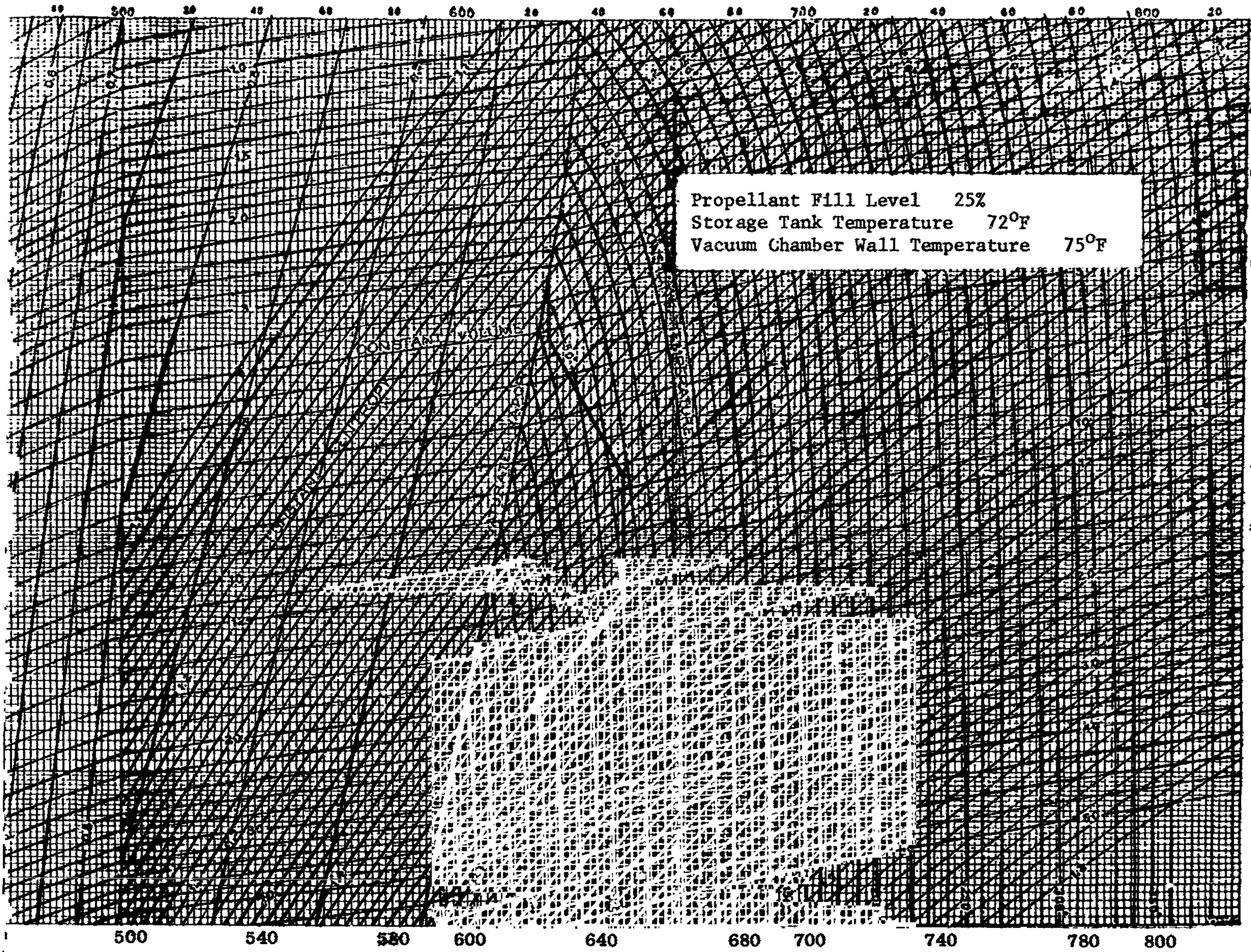
Figure 20-E

FOLDOUT FRAME



Pressure-Enthalpy

Figure 20-



ıre-Enthalpy Diagram

Heat Content - Btu. Per Lb.

Figure 20-F.

FOLDOUT FRAME

FOL... FRAME

temperature and vapor pressure drops below an acceptable value for proper operation of the attitude control thrusters.

The gas generation demand on the feed system was a nominal 6.3×10^{-3} lb/sec. The system utilized two 0.315 lb_f thrusters, which simulated single axis attitude control. The system performance test demonstrated that this system possessed the capability to generate the vapor to supply two thrusters simultaneously at a nominal thrust level of 0.315 lb_f for the required 18.2 seconds duration, but that adequate downstream pressure regulation is required to meet the demand.

Vendors have been identified who can supply the aluminum propellant tank and a properly designed pressure regulator for control of the thruster chamber pressure.

RECOMMENDATIONS

This study indicates a simple, logical solution to the problem of ammonia vaporization for cold and warm gas space propulsion, and it is recommended that it be continued.

The next phase of the study should be the construction of an aluminum tank and heat exchanger, equipped with appropriately calibrated throttle valve, a high quality pressure regulator, and suitable other valves, thrusters, and instrumentation, to systematically map the performance of the feed system as a prerequisite to flight design. At the same time flight qualified components should be tested for durability and reliability, and be on hand for use in the final flight design.

H. NEW TECHNOLOGY

Although the throttle valve is certainly not a new item of manufacture, its application here has a certain amount of novelty. The advantage lies in the fact that an appropriately designed throttle valve bypasses the problem of whether liquid or vapor is withdrawn from the propellant tank at zero gravity, since it will accept either and maintain within reasonable limits the desired pressure drop.

I. SUB-SCALE FEED SYSTEM TESTS

1. REASON FOR SUB-SCALE TESTS

Early in the program, prior to the formulation of the passive vaporization feed system configuration, some experiments were conducted on small diameter spherical ammonia storage tanks. The experiments sought to determine quantitatively the amount of ammonia that could be passively vaporized, as a function of tank volumetric capacity and surface area. The conclusions drawn from these tests were the following:

A. Design a heat exchanger to utilize waste heat.

B. Use a simple single pass tube type heat exchanger attached to the wall of the storage tank.

C. Zero-g problems of entrained liquid droplets should be solved by the heat exchanger helical flow path.

D. Write a computer program to size the heat exchanger.

2. HARDWARE BUILT

The above conclusions followed except that the decision was made to build a sub-scale version of the feed system and examine its performance prior to building the flight size with the 18-inch diameter storage tank. The hardware built was fairly crude and consisted of a cylindrical stainless steel tank with 75 feet of 0.060 I.D. tubing soldered onto its exterior surface. See Figure 21 for a photo of the hardware.

3. TEST RESULTS

The final test results confirmed the heat exchanger concept. The results of temperature instrumentation attached to the wall of the heat exchanger tubing revealed that the length of tubing used to achieve the vaporization and provide superheated gas was approximately 60% less than the amount the computer program predicted. The tests confirmed the throttle valve concept, and provided the type of information needed to make a prediction of the heat exchanger size needed for the full-scale 18-inch laboratory prototype feed system.

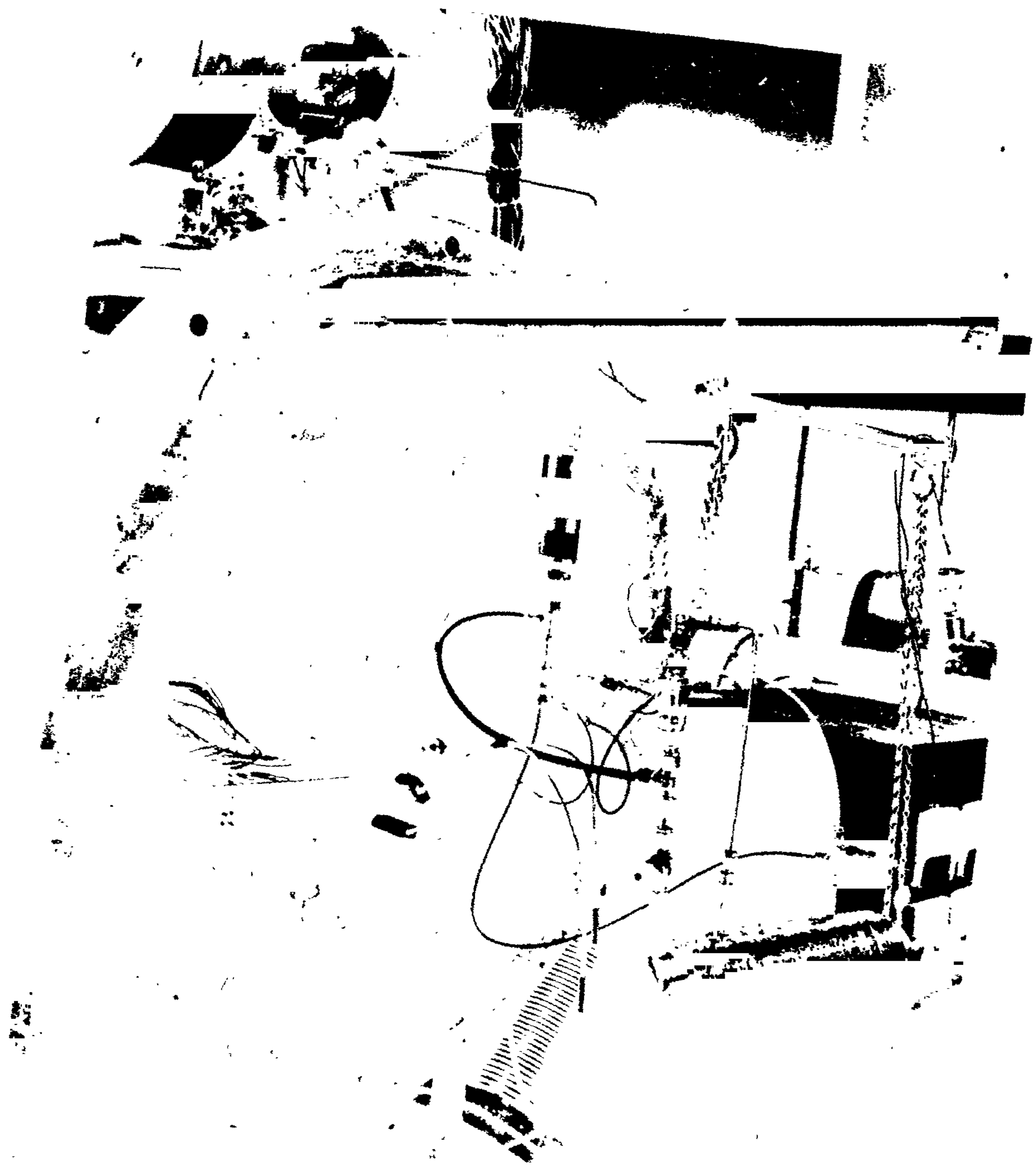


Figure 21. Sub-Scale Test Hardware in Vacuum Tank.

J. COMPUTER OUTPUT SHEET FOR AMMONIA HEAT EXCHANGER DESIGN

AMMONIA VAPORIZER

INPUT CONDITIONS

Wall Temperature	=	35.0 Degrees F.
Ammonia Inlet Temperature	=	27.0 Degrees F.
Ammonia Exit Temperature	=	7.8 Degrees F.
Ammonia Inlet Pressure	=	55.2 PSIA
Ammonia Exit Pressure	=	29.2 PSIA
Pressure Difference at the Inlet	=	11.6 PSI
Pressure Difference Along the Tube	=	26.0 PSI
Ammonia Flow Rate	=	0.0063 LB/SEC
Ammonia Mass Velocity	=	21.1 LB/(SEC-FT2)

OPTIMIZATION VALUES

Length of the Vaporizer	=	1513.6 Inches
Diameter, Inside of the Tube	=	0.234 Inches
Total Length	=	3597.7 Inches
Heat Flux	=	1590 BTU/(HR-FT2)

Convergence = 0.086, Number of Iterations = 64

K. STORAGE TANK/HEAT EXCHANGER BRAZING SPECIFICATION

1. Furnace braze 125 feet of 0.250 O.C. x 0.010 wall type 304 stainless steel tubing in a helical pattern onto the exterior surface of an 18 200 inch O.D. type 304 stainless steel sphere.

2. Commence with a 6-inch diameter coil of tubing (leaving a 12-inch loose end) concentric with one of the sphere fill tubes and progressively wrap the tubing with a coil of approximately 6-inch diameter, and leaving a 12-inch loose end. The spacing between tubes shall be approximately 3/8 inch.

3. Maximum intimate contact between tube and sphere plus minimum braze alloy weight is the primary concern. Structural strength of the braze joint is secondary.

4. All braze joints shall be reasonably smooth and uniform in appearance, forming smooth even fillets.

5. The maximum length of any single fillet defect shall not exceed 1/4 inch. Total amount of void shall not exceed 5 per cent.

6. The maximum errosion of the tube wall shall not exceed 2 mils.

L. STORAGE TANK/HEAT EXCHANGER BRAZING TECHNIQUE

The fabrication and brazing technique to be used by the Vac-Hyd Processing Company, Detroit, Michigan is outlined in the following steps:

A. The steel sphere is placed in a cradle resting fixture (with equatorial weld joint in a vertical plane) for the wrapping of the heat exchanger tubing. The cradle fixture allows the storage sphere to be supported without excessive point contact forces being exerted on the sphere or tubes.

B. The tubing is then hand wrapped onto the surface of the sphere. The tubing is securely held in contact with the sphere surface while wrapping by spot welding small stainless steel foil saddles (type 321, 0.005 thick) at appropriate intervals, over the tubing and to the sphere.

C. The tubing is wrapped in a helical pattern, concentric with the sphere fill and drain tubes.

D. When the tubing is completely wrapped, the sphere is placed in the brazing furnace and heated to approximately 1950°F whereupon the tubing is stress relieved (annealed). The sphere is removed from the furnace and following cooling, the tubing is tightened securely to the sphere wherever any relaxation has occurred. Additional foil saddles and/or repositioning of foil saddles may be required at this time. The foil saddles remain attached to the sphere throughout all subsequent processing.

E. The braze alloy selected is a nickel base per AMS 4777, and is applied at the sphere-tube fillet while in a slurry consistency.

F. The final operation is placing the storage sphere into the brazing furnace and executing the braze cycle.

M. THRUSTER NOZZLE PERFORMANCE AS A FUNCTION OF VARIABLE VACUUM CHAMBER AMBIENT PRESSURE

1. Ambient Pressure - Zero millimeters of mercury (Limit: 10 microns). Note predicted thruster performance, Figure 22 , where thrust is underlined and ambient pressure is circled. Nozzle degradation - 0%.

2. Ambient Pressure - 10 millimeters of mercury (10,000 microns). Note predicted thruster performance, Figure 23 , where thrust is underlined and ambient pressure is circled. Nozzle degradation - 9.85%

3. Ambient Pressure - 20 millimeters of mercury (20,000 microns). Note predicted thruster performance, Figure 24 , where thrust is underlined and ambient pressure is circuled. Nozzle degradation - 19.7%

NOZZLE OFF DESIGN CALCULATIONS

JPL THRUSTER

NOZZLE NUMBER 1 PROPELLANT AMMO

DESIGN SPECIFICATIONS

NOZZLE DATA

THROAT RADIUS	5.2900E-02 IN	ACTUAL EXIT RADIUS
IDEAL LENGTH	5.2500E-01 IN	MAXIMUM DIVERGENT ANG
CONVERGENT RADIUS	7.4060E-02 IN	DIVERGENT RADIUS
WALL TEMPERATURE	5.1000E 02 DEG R	THROAT AREA

THERMODYNAMIC DATA

STAGNATION PRESSURE	1.5000E 00 ATM	AMBIENT PRESSURE
STAGNATION TEMPERATURE	5.2000E 02 DEG R	AMBIENT TEMPERATURE
FLOW PER UNIT THROAT AREA	3.8609E-01 LB/SEC-IN2	THROAT TEMPERATURE
IDEAL SPECIFIC IMPULSE	1.0413E 02 SEC	THERMODYNAMIC EFFICIE
SPECIFIC GAS CONSTANT	1.1652E-01 B/LB-DEG R	ENERGY ADDITION PER F
FLOW PER POWER	1.9219E-01 LB/SEC-KW	OPTIMUM THRUST
WEIGHT FLOW RATE	3.3943E-03 LB/SEC	POWER

DISTANCE FROM THROAT IN	EFFECTIVE AREA RATIO	PRESSURE RATIO	BOUNDARY LAYER THICKNESS IN	ADJUSTED RADIUS IN	OVERALL EFFICIENCY	HEAT TRANSF Q B/SEC
5.0000E-03	1.0228E 00	2.2189E 00	1.6606E-04	5.3557E-02	2.1723E 01	4.6194E
1.0000E-02	1.0972E 00	2.9953E 00	2.6292E-04	5.5504E-02	1.8750E 01	7.3362E
1.5000E-02	1.2127E 00	3.8949E 00	3.5057E-04	5.8383E-02	1.5715E 01	9.2963E
2.0000E-02	1.3312E 00	4.7589E 00	4.2982E-04	6.1195E-02	1.6377E 01	1.0901E
2.5000E-02	1.4519E 00	5.6459E 00	5.0277E-04	6.3935E-02	1.7102E 01	1.2279E
3.0000E-02	1.5748E 00	6.5723E 00	5.7110E-04	6.6608E-02	1.7805E 01	1.3499E
3.5000E-02	1.6997E 00	7.5442E 00	6.3600E-04	6.9219E-02	1.8476E 01	1.4605E
4.0000E-02	1.8264E 00	8.5637E 00	6.9830E-04	7.1773E-02	1.9114E 01	1.5623E
4.5000E-02	1.9548E 00	9.6316E 00	7.5859E-04	7.4273E-02	1.9720E 01	1.6572E
5.0000E-02	2.0849E 00	1.0748E 01	8.1732E-04	7.6723E-02	2.0294E 01	1.7464E
5.5000E-02	2.2165E 00	1.1913E 01	8.7482E-04	7.9125E-02	2.0840E 01	1.8309E
6.0000E-02	2.3495E 00	1.3126E 01	9.3136E-04	8.1483E-02	2.1359E 01	1.9114E
6.5000E-02	2.4839E 00	1.4387E 01	9.8712E-04	8.3799E-02	2.1854E 01	1.9884E
7.0000E-02	2.6196E 00	1.5695E 01	1.0423E-03	8.6075E-02	2.2325E 01	2.0625E
7.5000E-02	2.7565E 00	1.7048E 01	1.0970E-03	8.8312E-02	2.2774E 01	2.2236E
8.5000E-02	3.0338E 00	1.9893E 01	1.2051E-03	9.2682E-02	2.3510E 01	2.3562E
9.5000E-02	3.3153E 00	2.2916E 01	1.3125E-03	9.6921E-02	2.4288E 01	2.6411E
1.1500E-01	3.8897E 00	2.9478E 01	1.5268E-03	1.0505E-01	2.5489E 01	3.1553E
1.5500E-01	5.0762E 00	4.4550E 01	1.9627E-03	1.2015E-01	2.7449E 01	3.5311E
1.9500E-01	6.3027E 00	6.2026E 01	2.4106E-03	1.3403E-01	2.9238E 01	3.8673E
2.3500E-01	7.5605E 00	8.1717E 01	2.8720E-03	1.4696E-01	3.0653E 01	4.1732E
2.7500E-01	8.8439E 00	1.0347E 02	3.3472E-03	1.5911E-01	3.1802E 01	4.4549E
3.1500E-01	1.0149E 01	1.2714E 02	3.8360E-03	1.7061E-01	3.2756E 01	4.7165E
3.5500E-01	1.1471E 01	1.5264E 02	4.3377E-03	1.8156E-01	3.3562E 01	4.9613E
3.9500E-01	1.2810E 01	1.7985E 02	4.8519E-03	1.9204E-01	3.4253E 01	5.1915E
4.3500E-01	1.4162E 01	2.0871E 02	5.3780E-03	2.0212E-01	3.4853E 01	5.4092E
4.7500E-01	1.5526E 01	2.3914E 02	5.9154E-03	2.1182E-01	3.5379E 01	5.6157E
5.1500E-01	1.6901E 01	2.7107E 02	6.4637E-03	2.2120E-01	3.5845E 01	5.8124E
5.2500E-01	1.7246E 01	2.7928E 02	6.6014E-03	2.2350E-01	3.6037E 01	5.8611E

Figure 22. Thruster Performance.

FOLDOUT FRAME

PROPELLANT AMMONIA NON DISSOCIATED

ICATIONS

TA

TUAL EXIT RADIUS	2,2350E=01	IN
IMUM DIVERGENT ANGLE	3,0000E 01	DEG
/ERGENT RADIUS	2,1160E=02	IN
ROAT AREA	8,7915E=03	IN2

DATA

BIENT PRESSURE	0,	MM HG
BIENT TEMPERATURE	5,1000E 02	DEG R
ROAT TEMPERATURE	4,4892E 02	DEG R
ERMODYNAMIC EFFICIENCY	4,5479E 01	
ERGY ADDITION PER POUND	4,9331E 00	B/LB
TIMUM THRUST	3,5345E=01	LB
WER	1,7661E=02	KW

OVERALL FFICIENCY	HEAT TRANSFER Q B/SEC	EFFECTIVE SPECIFIC IMPULSE SEC	ACTUAL THRUST LB	MACH NUMBER
.1723E	4,6194E-05	7,1968E 01	2,4428E-01	1,1516E 00
.8750E 01	7,3362E-05	6,6862E 01	2,2695E-01	1,3746E 00
.5715E 01	9,2963E-05	6,1211E 01	2,0777E-01	1,5543E 00
.6377E 01	1,0901E-04	6,2488E 01	2,1210E-01	1,6855E 00
.7102E 01	1,2279E-04	6,3856E 01	2,1674E-01	1,7945E 00
.7805E 01	1,3499E-04	6,5155E 01	2,2115E-01	1,8898E 00
.8476E 01	1,4605E-04	6,6372E 01	2,2528E-01	1,9754E 00
.9114E 01	1,5623E-04	6,7508E 01	2,2914E-01	2,0534E 00
.9720E 01	1,6572E-04	6,8569E 01	2,3274E-01	2,1255E 00
.0294E 01	1,7464E-04	6,9561E 01	2,3611E-01	2,1925E 00
.0840E 01	1,8309E-04	7,0490E 01	2,3926E-01	2,2553E 00
.1359E 01	1,9114E-04	7,1363E 01	2,4223E-01	2,3144E 00
.1854E 01	1,9884E-04	7,2184E 01	2,4501E-01	2,3703E 00
.2325E 01	2,0625E-04	7,2957E 01	2,4764E-01	2,4235E 00
.2774E 01	2,2236E-04	7,3688E 01	2,5012E-01	2,4741E 00
.3510E 01	2,3562E-04	7,4870E 01	2,5413E-01	2,5687E 00
.4288E 01	2,6411E-04	7,6098E 01	2,5830E-01	2,6559E 00
.5489E 01	3,1553E-04	7,7956E 01	2,6461E-01	2,8125E 00
.7449E 01	3,5311E-04	8,0898E 01	2,7459E-01	3,0744E 00
.9238E 01	3,8673E-04	8,3493E 01	2,8340E-01	3,2899E 00
.0653E 01	4,1732E-04	8,5490E 01	2,9018E-01	3,4742E 00
.1802E 01	4,4549E-04	8,7078E 01	2,9557E-01	3,6356E 00
.2756E 01	4,7165E-04	8,8374E 01	2,9997E-01	3,7797E 00
.3562E 01	4,9613E-04	8,9455E 01	3,0363E-01	3,9101E 00
.4253E 01	5,1915E-04	9,0371E 01	3,0674E-01	4,0293E 00
.4853E 01	5,4092E-04	9,1159E 01	3,0942E-01	4,1393E 00
.5379E 01	5,6157E-04	9,1844E 01	3,1174E-01	4,2416E 00
.5845E 01	5,8124E-04	9,2447E 01	3,1379E-01	4,3371E 00
.6037E 01	5,8611E-04	9,2694E 01	3,1463E-01	4,3601E 00

ster Performance.

FOLDOUT FRAME

FOLDOUT FRAME

NOZZLE OFF DESIGN CALCULATIONS

JPL THRUSTER

NOZZLE NUMBER 1 PROPELLANT AM

DESIGN SPECIFICATIONS

NOZZLE DATA

THROAT RADIUS	5,2900E-02 IN	ACTUAL EXIT RADIUS	
IDEAL LENGTH	5,2500E-01 IN	MAXIMUM DIVERGENT A	
CONVERGENT RADIUS	7,4060E-02 IN	DIVERGENT RADIUS	
WALL TEMPERATURE	5,1000E 02 DEG R	THROAT AREA	

THERMODYNAMIC DATA

STAGNATION PRESSURE	1,5000E 00 ATM	AMBIENT PRESSURE	
STAGNATION TEMPERATURE	5,2000E 02 DEG R	AMBIENT TEMPERATURE	
FLOW PER UNIT THROAT AREA	3,8609E-01 LB/SEC-IN2	THROAT TEMPERATURE	
IDEAL SPECIFIC IMPULSE	1,0413E 02 SEC	THERMODYNAMIC EFFIC	
SPECIFIC GAS CONSTANT	1,1652E-01 B/LB-DEG R	ENERGY ADDITION PEF	
FLOW PER POWER	1,9219E-01 LB/SEC-KW	OPTIMUM THRUST	
WEIGHT FLOW RATE	3,3943E-03 LB/SEC	POWER	

DISTANCE FROM THROAT IN	EFFECTIVE AREA RATIO	PRESSURE RATIO	BOUNDARY LAYER THICKNESS IN	ADJUSTED RADIUS IN	OVERALL EFFICIENCY	HEA TRANS Q B/SE
5,0000E-03	1,0228E 00	2,2189E 00	1,6606E-04	5,3557E-02	2.1415E 01	4,619
1,0000E-02	1,0972E 00	2,9953E 00	2,6292E-04	5,5504E-02	1.8442E 01	7,336
1,5000E-02	1,2127E 00	3,8949E 00	3,5057E-04	5,8383E-02	1.5403E 01	9,296
2,0000E-02	1,3312E 00	4,7589E 00	4,2982E-04	6,1195E-02	1,6028E 01	1,090
2,5000E-02	1,4519E 00	5,6459E 00	5,0277E-04	6,3935E-02	1,6712E 01	1,227
3,0000E-02	1,5748E 00	6,5723E 00	5,7110E-04	6,6608E-02	1,7374E 01	1,349
3,5000E-02	1,6997E 00	7,5442E 00	6,3600E-04	6,9219E-02	1.8002E 01	1,460
4,0000E-02	1,8264E 00	8,5637E 00	6,9830E-04	7,1773E-02	1,8596E 01	1,562
4,5000E-02	1,9548E 00	9,6316E 00	7,5859E-04	7,4273E-02	1.9156E 01	1,657
5,0000E-02	2,0849E 00	1,0748E 01	8,1732E-04	7,6723E-02	1,9684E 01	1,746
5,5000E-02	2,2165E 00	1,1913E 01	8,7482E-04	7,9125E-02	2,0183E 01	1,830
6,0000E-02	2,3495E 00	1,3126E 01	9,3136E-04	8,1483E-02	2,0654E 01	1,911
6,5000E-02	2,4839E 00	1,4387E 01	9,8712E-04	8,3799E-02	2,1099E 01	1,988
7,0000E-02	2,6196E 00	1,5695E 01	1,0423E-03	8,6075E-02	2,1521E 01	2,062
7,5000E-02	2,7565E 00	1,7048E 01	1,0970E-03	8,8312E-02	2,1920E 01	2,223
8,5000E-02	3,0338E 00	1,9893E 01	1,2051E-03	9,2682E-02	2,2555E 01	2,356
9,5000E-02	3,3153E 00	2,2916E 01	1,3125E-03	9,6921E-02	2,3227E 01	2,641
1,1500E-01	3,8897E 00	2,9478E 01	1,5268E-03	1,0505E-01	2,4214E 01	3,155
1,5500E-01	5,0762E 00	4,4550E 01	1,9627E-03	1,2015E-01	2,5724E 01	3,531
1,9500E-01	6,3027E 00	6,2026E 01	2,4106E-03	1,3403E-01	2,7030E 01	3,867
2,3500E-01	7,5605E 00	8,1717E 01	2,8720E-03	1,4696E-01	2,7945E 01	4,173
2,7500E-01	8,8439E 00	1,0347E 02	3,3472E-03	1,5911E-01	2,8580E 01	4,454

SHOCK HAS OCCURED

3.1500E-01	1,0149E 01	1.2714E 02	3,8360E-03	1.7061E-01	2,9010E 01	4,716
3,5500E-01	1.1471E 01	1,5264E 02	4,3377E-03	1.8156E-01	2.9283E 01	4,961
3,9500E-01	1,2810E 01	1,7985E 02	4,8519E-03	1,9204E-01	2.9434E 01	5,191
4.3500E-01	1,4162E 01	2,0871E 02	5,3780E-03	2,0212E-01	2,9489E 01	5,40
4,7500E-01	1,5526E 01	2,3914E 02	5,9154E-03	2,1182E-01	2,9465E 01	5,61
5,1500E-01	1,6901E 01	2,7107E 02	6,4637E-03	2,2120E-01	2,9378E 01	5,812
5,2500E-01	1,7246E 01	2,7928E 02	6,6014E-03	2,2350E-01	2.9423E 01	5,861

FOLDOUT FRAME

Figure 23. Thruster Performanc

ZZLE NUMBER 1 PROPELLANT AMMONIA NON DISSOCIATED

DESIGN SPECIFICATIONS

NOZZLE DATA

	ACTUAL EXIT RADIUS	2.2350E-01 IN
	MAXIMUM DIVERGENT ANGLE	3.0000E 01 DEG
	DIVERGENT RADIUS	2.1160E-02 IN
G R	THROAT AREA	8.7915E-03 IN2

THERMODYNAMIC DATA

M	AMBIENT PRESSURE	1.0000E 01 MM HG
EG R	AMBIENT TEMPERATURE	5.1000E 02 DEG R
/SEC-IN2	THROAT TEMPERATURE	4.4892E 02 DEG R
EC	THERMODYNAMIC EFFICIENCY	4.5479E 01
LB-DEG R	ENERGY ADDITION PER POUND	4.9331E 00 B/LB
/SEC-KW	OPTIMUM THRUST	3.5345E-01 LB
/SEC	POWER	1.7661E-02 KW

NDARY LAYER CKNESS IN	ADJUSTED RADIUS IN	OVERALL EFFICIENCY	HEAT TRANSFER Q B/SEC	EFFECTIVE SPECIFIC IMPULSE SEC	ACTUAL THRUST LB	MACH NUMBER
06E-04	5.3557E-02	2.1415E 01	4.6194E-05	7.1455E 01	2.4254E-01	1.1516E 00
92E-04	5.5504E-02	1.8442E 01	7.3362E-05	6.6311E 01	2.2508E-01	1.3746E 00
57E-04	5.8383E-02	1.5403E 01	9.2963E-05	6.0602E 01	2.0570E-01	1.5543E 00
82E-04	6.1195E-02	1.6028E 01	1.0901E-04	6.1818E 01	2.0983E-01	1.6855E 00
77E-04	6.3935E-02	1.6712E 01	1.2279E-04	6.3124E 01	2.1426E-01	1.7945E 00
10E-04	6.6608E-02	1.7374E 01	1.3499E-04	6.4361E 01	2.1846E-01	1.8898E 00
00E-04	6.9219E-02	1.8002E 01	1.4605E-04	6.5514E 01	2.2237E-01	1.9754E 00
30E-04	7.1773E-02	1.8596E 01	1.5623E-04	6.6586E 01	2.2601E-01	2.0534E 00
59E-04	7.4273E-02	1.9156E 01	1.6572E-04	6.7582E 01	2.2939E-01	2.1255E 00
732E-04	7.6723E-02	1.9684E 01	1.7464E-04	6.8508E 01	2.3253E-01	2.1925E 00
82E-04	7.9125E-02	2.0183E 01	1.8309E-04	6.9370E 01	2.3546E-01	2.2553E 00
36E-04	8.1483E-02	2.0654E 01	1.9114E-04	7.0175E 01	2.3819E-01	2.3144E 00
12E-04	8.3799E-02	2.1099E 01	1.9884E-04	7.0927E 01	2.4075E-01	2.3703E 00
423E-03	8.6075E-02	2.1521E 01	2.0625E-04	7.1632E 01	2.4314E-01	2.4235E 00
970E-03	8.8312E-02	2.1920E 01	2.2236E-04	7.2293E 01	2.4538E-01	2.4741E 00
051E-03	9.2682E-02	2.2555E 01	2.3562E-04	7.3333E 01	2.4891E-01	2.5687E 00
125E-03	9.6921E-02	2.3227E 01	2.6411E-04	7.4417E 01	2.5259E-01	2.6559E 00
268E-03	1.0505E-01	2.4214E 01	3.1553E-04	7.5982E 01	2.5790E-01	2.8125E 00
527E-03	1.2015E-01	2.5724E 01	3.5311E-04	7.8315E 01	2.6582E-01	3.0744E 00
106E-03	1.3403E-01	2.7030E 01	3.8673E-04	8.0279E 01	2.7249E-01	3.2899E 00
720E-03	1.4696E-01	2.7945E 01	4.1732E-04	8.1626E 01	2.7706E-01	3.4742E 00
472E-03	1.5911E-01	2.8580E 01	4.4549E-04	8.2549E 01	2.8019E-01	3.6356E 00
360E-03	1.7061E-01	2.9010E 01	4.7165E-04	8.3167E 01	2.8229E-01	3.7797E 00
377E-03	1.8156E-01	2.9283E 01	4.9613E-04	8.3557E 01	2.8362E-01	3.9101E 00
519E-03	1.9204E-01	2.9434E 01	5.1915E-04	8.3773E 01	2.8435E-01	4.0293E 00
780E-03	2.0212E-01	2.9489E 01	5.4092E-04	8.3850E 01	2.8461E-01	4.1393E 00
154E-03	2.1182E-01	2.9465E 01	5.6157E-04	8.3817E 01	2.8450E-01	4.2416E 00
637E-03	2.2120E-01	2.9378E 01	5.8124E-04	8.3692E 01	2.8408E-01	4.3371E 00
014E-03	2.2350E-01	2.9423E 01	5.8611E-04	8.3757E 01	2.8429E-01	4.3601E 00

Figure 23. Thruster Performance

NOZZLE OFF DESIGN CALCULATIONS

JPL THRUSTER

NOZZLE NUMBER 1 PROPELLANT AMM

DESIGN SPECIFICATIONS

NOZZLE DATA

THROAT RADIUS	5.2900E-02 IN	ACTUAL EXIT RADIUS
IDEAL LENGTH	5.2500E-01 IN	MAXIMUM DIVERGENT AN
CONVERGENT RADIUS	7.4060E-02 IN	DIVERGENT RADIUS
WALL TEMPERATURE	5.1000E 02 DEG R	THROAT AREA

THERMODYNAMIC DATA

STAGNATION PRESSURE	1.5000E 00 ATM	AMBIENT PRESSURE
STAGNATION TEMPERATURE	5.2000E 02 DEG R	AMBIENT TEMPERATURE
FLOW PER UNIT THROAT AREA	3.8609E-01 LB/SEC-IN2	THROAT TEMPERATURE
IDEAL SPECIFIC IMPULSE	1.0413E 02 SEC	THERMODYNAMIC EFFICI
SPECIFIC GAS CONSTANT	1.1652E-01 B/LB-DEG R	ENERGY ADDITION PER
FLOW PER POWER	1.9219E-01 LB/SEC-KW	OPTIMUM THRUST
WEIGHT FLOW RATE	3.3943E-03 LB/SEC	POWER

DISTANCE FROM THROAT IN	EFFECTIVE AREA RATIO	PRESSURE RATIO	BOUNDARY LAYER THICKNESS IN	ADJUSTED RADIUS IN	OVERALL EFFICIENCY	HEAT TRANSF Q B/SEC
5.0000E-03	1.0228E 00	2.2189E 00	1.6606E-04	5.3557E-02	2.1108E 01	4.6194E
1.0000E-02	1.0972E 00	2.9953E 00	2.6292E-04	5.5504E-02	1.8137E 01	7.3362E
1.5000E-02	1.2127E 00	3.8949E 00	3.5057E-04	5.8383E-02	1.5095E 01	9.2963E
2.0000E-02	1.3312E 00	4.7589E 00	4.2982E-04	6.1195E-02	1.5682E 01	1.0901E
2.5000E-02	1.4519E 00	5.6459E 00	5.0277E-04	6.3935E-02	1.6327E 01	1.2279E
3.0000E-02	1.5748E 00	6.5723E 00	5.7110E-04	6.6608E-02	1.6948E 01	1.3499E
3.5000E-02	1.6997E 00	7.5442E 00	6.3600E-04	6.9219E-02	1.7534E 01	1.4605E
4.0000E-02	1.8264E 00	8.5637E 00	6.9830E-04	7.1773E-02	1.8084E 01	1.5623E
4.5000E-02	1.9548E 00	9.6316E 00	7.5859E-04	7.4273E-02	1.8601E 01	1.6572E
5.0000E-02	2.0849E 00	1.0748E 01	8.1732E-04	7.6723E-02	1.9084E 01	1.7464E
5.5000E-02	2.2165E 00	1.1913E 01	8.7482E-04	7.9125E-02	1.9537E 01	1.8309E
6.0000E-02	2.3495E 00	1.3126E 01	9.3136E-04	8.1483E-02	1.9961E 01	1.9114E
6.5000E-02	2.4839E 00	1.4387E 01	9.8712E-04	8.3799E-02	2.0359E 01	1.9884E
7.0000E-02	2.6196E 00	1.5695E 01	1.0423E-03	8.6075E-02	2.0732E 01	2.0625E
7.5000E-02	2.7565E 00	1.7048E 01	1.0970E-03	8.8312E-02	2.1082E 01	2.2236
8.5000E-02	3.0338E 00	1.9893E 01	1.2051E-03	9.2682E-02	2.1620E 01	2.3562
9.5000E-02	3.3153E 00	2.2916E 01	1.3125E-03	9.6921E-02	2.2190E 01	2.6411E
1.1500E-01	3.8897E 00	2.9478E 01	1.5268E-03	1.0505E-01	2.2972E 01	3.1553E
1.5500E-01	5.0762E 00	4.4550E 01	1.9627E-03	1.2015E-01	2.4055E 01	3.5311

SHOCK HAS OCCURED

DISTANCE FROM THROAT IN	EFFECTIVE AREA RATIO	PRESSURE RATIO	BOUNDARY LAYER THICKNESS IN	ADJUSTED RADIUS IN	OVERALL EFFICIENCY	HEAT TRANSF Q B/SEC
1.9500E-01	6.3027E 00	6.2026E 01	2.4106E-03	1.3403E-01	2.4909E 01	3.8673
2.3500E-01	7.5695E 00	8.1717E 01	2.8720E-03	1.4696E-01	2.5362E 01	4.1732
2.7500E-01	8.8439E 00	1.0347E 02	3.3472E-03	1.5911E-01	2.5530E 01	4.4549
3.1500E-01	1.0149E 01	1.2714E 02	3.8360E-03	1.7061E-01	2.5491E 01	4.7165E
3.5500E-01	1.1471E 01	1.5264E 02	4.3377E-03	1.8156E-01	2.5295E 01	4.9613
3.9500E-01	1.2810E 01	1.7985E 02	4.8519E-03	1.9204E-01	2.4980E 01	5.1915
4.3500E-01	1.4162E 01	2.0871E 02	5.3780E-03	2.0212E-01	2.4572E 01	5.4092
4.7500E-01	1.5526E 01	2.3914E 02	5.9154E-03	2.1182E-01	2.4091E 01	5.6157
5.1500E-01	1.6901E 01	2.7107E 02	6.4637E-03	2.2120E-01	2.3553E 01	5.8124
5.2500E-01	1.7246E 01	2.7928E 02	6.6014E-03	2.2350E-01	2.3479E 01	5.8611

FOLDOUT FRAME

Figure 24. Thruster Performanc

```
UMBER  1            PROPELLANT  AMMONIA NON DISSOCIATED
  DESIGN SPECIFICATIONS
       NOZZLE DATA
              ACTUAL EXIT RADIUS                 2,2350E-01 IN
              MAXIMUM DIVERGENT ANGLE            3,0000E 01 DEG
              DIVERGENT RADIUS                   2.1160E-02 IN
              THROAT AREA                        8.7915E-03 IN2

    THERMODYNAMIC DATA
              AMBIENT PRESSURE                   2,0000E 01 MM HG
              AMBIENT TEMPERATURE                5,1000E 02 DEG R
              THROAT TEMPERATURE                 4,4892E 02 DEG R
              THERMODYNAMIC EFFICIENCY           4,5479E 01
              ENERGY ADDITION PER POUND          4,9331E 00 B/LB
              OPTIMUM THRUST                     3,5345E-01 LB
              POWER                              1,7661E-02 KW
```

ADJUSTED RADIUS IN	OVERALL EFFICIENCY	HEAT TRANSFER Q B/SEC	EFFECTIVE SPECIFIC IMPULSE SEC	ACTUAL THRUST LB	MACH NUMBER
5,3557E-02	2.1108E 01	4,6194E-05	7,0942E 01	2,4080E-01	1,1516E 00
5,5504E-02	1,8137E 01	7,3362E-05	6,5760E 01	2,2321E-01	1,3746E 00
5,8383E-02	1.5095E 01	9,2963E-05	5,9992E 01	2,0363E-01	1,5543E 00
6,1195E-02	1.5682E 01	1,0901E-04	6,1148E 01	2,0755E-01	1,6855E 00
6,3935E-02	1.6327E 01	1,2279E-04	6,2393E 01	2,1178E-01	1,7945E 00
6,6608E-02	1.6948E 01	1,3499E-04	6,3567E 01	2,1576E-01	1,8898E 00
6.9219E-02	1,7534E 01	1,4605E-04	6,4657E 01	2,1946E-01	1,9754E 00
7,1773E-02	1.8084E 01	1,5623E-04	6,5665E 01	2,2288E-01	2,0534E 00
7.4273E-02	1.8601E 01	1,6572E-04	6,6595E 01	2,2604E-01	2,1255E 00
7.6723E-02	1.9084E 01	1,7464E-04	6,7455E 01	2,2896E-01	2.1925E 00
7.9125E-02	1.9537E 01	1,8309E-04	6,8250E 01	2,3166E-01	2,2553E 00
8.1483E-02	1.9961E 01	1,9114E-04	6,8987E 01	2,3416E-01	2,3144E 00
8.3799E-02	2.0359E 01	1,9884E-04	6,9671E 01	2,3648E-01	2,3703E 00
8.6075E-02	2.0732E 01	2,0625E-04	7,0306E 01	2,3864E-01	2,4235E 00
8,8312E-02	2.1082E 01	2,2236E-04	7,0898E 01	2,4065E-01	2,4741E 00
9,2682E-02	2,1620E 01	2,3562E-04	7,1796E 01	2,4370E-01	2,5687E 00
9,6921E-02	2.2190E 01	2,6411E-04	7,2736E 01	2,4689E-01	2,6559E 00
1.0505E-01	2.2972E 01	3,1553E-04	7,4008E 01	2,5120E-01	2,8125E 00
1,2015E-01	2.4055E 01	3,5311E-04	7,5732E 01	2,5706E-01	3,0744E 00
1,3403E-01	2.4909E 01	3,8673E-04	7,7065E 01	2,6158E-01	3,2899E 00
1,4696E-01	2.5362E 01	4,1732E-04	7,7762E 01	2,6395E-01	3,4742E 00
1,5911E-01	2.5530E 01	4,4549E-04	7,8020E 01	2.6482E-01	3,6356E 00
1.7061E-01	2.5491E 01	4,7165E-04	7,7959E 01	2,6462E-01	3,7797E 00
1.8156E-01	2.5295E 01	4,9613E-04	7,7659E 01	2,6360E-01	3.9101E 00
1,9204E-01	2,4980E 01	5,1915E-04	7,7174E 01	2,6195E-01	4,0293E 00
2.0212E-01	2.4572E 01	5,4092E-04	7,6542E 01	2.5980E-01	4,1393E 00
2,1182E-01	2.4091E 01	5,6157E-04	7,5789E 01	2,5725E-01	4.2416E 00
2.2120E-01	2.3553E 01	5,8124E-04	7,4938E 01	2,5436E-01	4,3371E 00
2,2350E-01	2.3479E 01	5.8611E-04	7,4820E 01	2,5396E-01	4,3601E 00

Figure 24. Thruster Performance. FOLDOUT FRAME

X. SPECIFICATION - VALVE, PRESSURE REGULATOR, PNEUMATIC (AMMONIA)

1. SCOPE

1.1 These specifications define the detail requirements and acceptance criteria for a pneumatic pressure regulator valve suitable for controlling ammonia gas. The application is for a spacecraft thruster system.

2. APPLICABLE DOCUMENTS

2.1 Applicability. The following documents in effect on date of invitation for bids form a part of this specification to the extent referenced herein. In the event of conflict between this specification and the documents referenced below, this specification shall govern.

2.2 Military Specifications

MIL-P-5514 Packings: Installation and Gland Design.

2.3 General Electric Specifications/Drawings.

SPPS 04-0001-00-A Component, General Specification for.

2.4 Other

ANA Bulletin 438 Age Controls for Age Sensitive Elastomeric Materials Federal Standard No. 209 Clean Room and Work Station Requirements for Controlled Environment.

3. REQUIREMENTS

3.1 General. The pressure regulator shall maintain outlet pressure within required limits for all specified variations in inlet pressure, flow demands, and short as well as long periods of lockup. The pressure regulator must also be capable of conformance with all specification requirements when subjected to any combination of operating environments and during the entire period of design lift. Materials used shall be compatible with the ammonia gas and specified environmental conditions. Compact size is important.

3.2 Acknowledgments. The vendor shall reference this specification in all quotations and all purchase order acknowledgments.

3.3 Design and Construction. All the requirements of SPPS Specification 04-0001-00-A apply unless otherwise noted.

3.3.1 Materials. All materials used shall be corrosion resistant or suitably protected against corrosion, and compatible with anhydrous ammonia and the environmental conditions specified herein.

3.3.2 "O" Ring. In the event any "O" rings must be used, the quantity shall be kept to a minimum. The "O" rings shall conform to the requirements of ANA Bulletin No. 438. Design criteria shall be in accordance with the requirements of MIL-P-5514.

3.3.3 Seat. Soft seat material is to be used and if any bonding agent is used, the effect of ammonia upon that agent must be known.

3.3.4 Seat Stabilization. All valve seats shall be stabilized to reduce variation in settings and operating characteristics under all environments, by subjecting the valve seats to a maximum working pressure at a temperature equal to or in excess of 125°F. The time duration shall be determined by the materials used and the application in the particular valve design. The vendor shall submit documentation outlining his material and procedures.

3.3.5 Lubricants. Unless othersize authorized by the Purchaser, no lubricating oils or greases shall be used in the regulator valve.

3.3.6 Filter. An integral inlet and outlet filter shall be provided to protect the regulator from contamination; the filter shall be a woven stainless steel wire type, capable of removing 98% of all solid particulate contaminants in excess of 10 microns and 100% in excess of 25 microns. The filter flow area shall be a minimum of 10 times the flow area of the valve seat restriction and shall be optimized to provide low pressure drop and adequate resistance to clogging.

The vendor shall perform tests and verify the integrity of the mesh element and the size of the mesh. Integrity means that no tears, breaks, open seams, enlarged openings and media migration occur within or from the filter.

3.3.7 Fittings. Inlet and outlet fittings shall be male, and of the AN type. Outlet to be sized for 1/4-inch OD tube, inlet for 1/4-inch OD tube.

3.4 Inlet Pressure. Inlet pressure to the regulators will vary from 30 to 220 psia.

3.5 Outlet Pressure. Approximately 22.25 psia.

3.5.1 The design of the regulator must be such that the outlet pressure setting can be readily adjusted ± 0.5 psia by either the vendor or by GE-SPPS.

3.6 Flow Rate. Zero to 6.3 x 10^{-3} lbs/sec continuously.

3.6.1 The gas flow rate range specified in Paragraph 3.6 represents system flow rate. The regulators may be physically capable of handling greater flow rates than the maximum of the range defined.

3.7 Pressure Regulation. For the output pressure setting, no more than 1% variation in output pressure level shall occur when the system in which the regulator is installed is operated with all other system parameters held constant except inlet pressure to the regulator.

3.8 Lockup Pressure. For the output pressure setting, no more than 5% variation in output pressure level shall occur for "no-flow" periods ranging from 0.015 seconds to 3 years. The pressure regulation tolerance and lockup pressure tolerance are independent and cannot be considered cumulative with respect to output pressure level variation during flow or non-flow conditions.

3.9 Response Time. With the regulator in the lockup condition, it shall take no more than 1 second to establish flow and regulate pressure within specified limits from the time a quick operating valve adjacent to the outlet port is fully opened. It shall take no more than 100 milliseconds to change from flow to lock-up pressure within specified limits from the time the quick operating valve is fully closed.

3.10 Leakage.

3.10.1 External Leakage. Not to exceed 5 x 10^{-7} std cc/sec of air.

3.11 Proof Pressure. The regulator shall be capable of withstanding a proof pressure of 350 psig without sustaining any damage or degradation of performance. The proof pressure capability is applicable for all individual tests or any combination of tests tabulated below.

3.11.1 Proof pressure of 350 psig applied at inlet fitting with outlet fitting open.

3.11.2 Proof pressure of 350 psig applied uniformly to all internal portions of the regulator.

3.12 Design Life. Over a three-year period and in the environment specified herein, the regulator shall meet all requirements during and after the equivalent of 50,000 cycles. A cycle is defined as a three-step sequence. With inlet pressure being maintained within specified limits, the outlet pressure set for one particular value within the range specified, the regulator is first in the lockup (no flow) condition as a result of a downstream valve being shut. Second, the downstream quick operating valve opens requiring the regulator to regulate pressure while flowing. The third and final step in the cycle returns the regulator to the lockup condition as the quick operating downstream valve shuts.

3.13 Environment.

3.13.1 Operating Environment. The regulator shall be capable of operating over the temperature range of 0°F to 100°F. Operating is required under space vacuum conditions for a period of three years. The ability to operate in zero gravity is required. Operating at standard atmospheric conditions in a gravity field with the regulator installed in any position is also required. The regulator will be tested in a space environment simulator which operates at 10^{-7} torr pressure. During its lifetime in orbit, the regulator will experience a vacuum of less than 10^{-12} mm Hg.

3.14 Cleanliness Procedures and Controls.

3.14.1 Assembly Cleaning. Immediately prior to the assembly operation, all parts which constitute the final assembly (including shipping covers, port closures, shipping bags, etc.) shall be thoroughly cleaned using procedures and equipment which will provide an assembly which is clean to the level specified herein. The gases and liquids used in this process shall have been passed, finally, through a 0.45 micron absolute filter. The cleaning equipment shall be so arranged that contamination cannot get into the immediate area of the parts being cleaned. Assembly or other tools which will come in contact with the parts being assembled shall be cleaned the same level as the parts. The parts shall be cleaned until the final rinse solution contains no more than the number of particles shown below per 100 ml of solution filtered through a standard HA millipore filter.

Contaminate Max. Dimension, Microns		Maximum Number Particles	
		Metallic	Non-Metallic
Less than	25	No Requirement	
Greater than	26	20	150
Greater than	50	10	50
Greater than	100	0	7
Greater than	350	Non-Allowable	

3.15 Shock Pressure. The regulator shall be capable of withstanding the shock pressure (of 200 psia) resulting from the opening of a normally closed explosive valve upstream of its inlet fitting without sustaining any damage or degradation of performance.

4. QUALITY ASSURANCE PROVISIONS

4.1 General. A Quality Control System shall be established and maintained by the vendor to assure that components are designed, manufactured and tested in accordance with this specification. To assure compliance with the Requirements of this specification, each production type component shall be subjected to the Acceptance Tests and Procedures defined herein.

4.2 Test Conditions and Facilities

4.2.1 Standard Test Conditions. Ambient conditions for conducting component performance tests shall be per room ambient.

4.2.2 Performance Tests. Performance tests shall be performed at standard ambient conditions to demonstrate the basic calibration and operating of the component. They shall consist of the test specified below:

Physical Examination	Pressure Reduction Test
Contamination Check	Gas Flow Test
Proof Pressure Test	Cycling Test followed by Leakage Test

5. PREPARATION FOR DELIVERY

The unit shall be prepared for delivery per GE-SPPS Specification 04-0001-00-A.

O. AMMONIA STORAGE TANK FILLING PROCEDURES

During the course of laboratory testing it was periodically necessary either to fill an empty storage tank or to replenish a partially filled storage tank. Certain problems must be considered when filling liquid ammonia storage vessels. The distillation technique, shown in Figure 25, is a very slow process and was rejected. This process requires reducing the temperature of the storage tank via ice bath below the temperature of the supply bottle. The gaseous ammonia is condensed to liquid at the cool surface of the storage tank.

A faster and more versatile technique for filling is to pressure feed liquid ammonia directly from an inverted supply bottle into the storage tank. This technique requires the use of a vacuum facility or vacuum pump. Refer to Figure 26, which illustrates this technique. The filling sequence is summarized as follows:

1. With valves B, C, and E closed, evacuate open lines through valve A and D to vacuum chamber.
2. Close valve D.
3. Open valve E. Lines will fill with liquid down to D and C.
4. Slowly crack open valve B to draw off NH_3 vapor from ullage
5. Crack open valve C to admit liquid NH_3 into storage tank. Regulate speed of filling by opening valve B to cause rapid drop of ullage pressure in storage tank, then open valve C further to supply greater quantities of liquid.

The liquid NH_3 is pressure fed by the supply bottle vapor pressure which is greater than the storage tank ullage pressure.

To cease filling and shut down, do the following:

1. Close valve B and C.
2. Close valve E.
3. Open valve D slowly to vent liquid NH_3 into vacuum chamber.
4. When all liquid NH_3 is evacuated from lines, close valves A and D.
5. Disconnect storage tank at valves B and C. In the laboratory set up valves B and C are retained with the storage tank at all times.

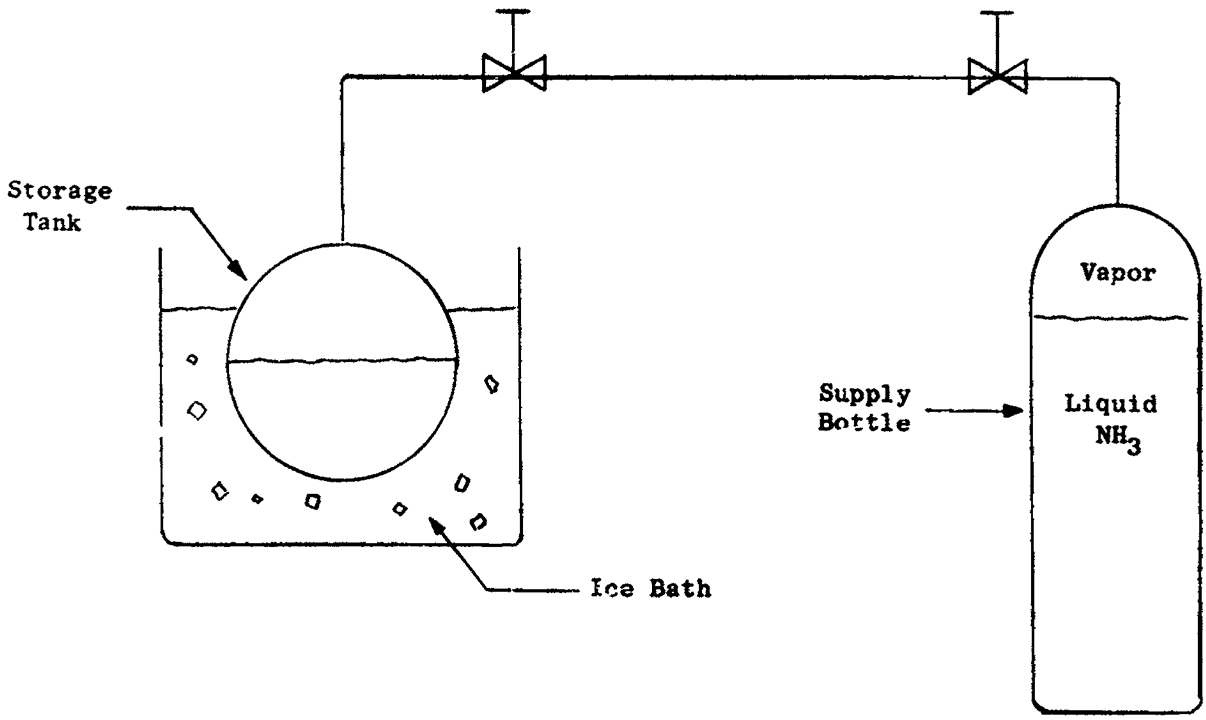


Figure 25. Ammonia Storage Tank Filling Set-up (Condensation Filling).

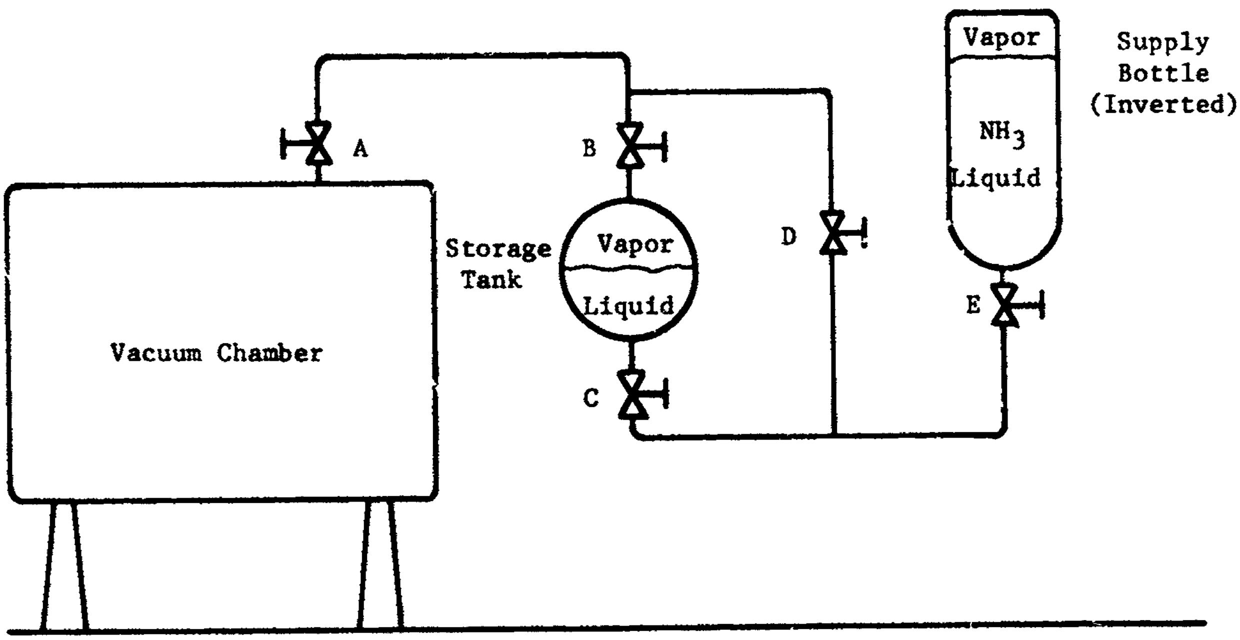


Figure 26. Ammonia Storage Tank Filling Set-up (Liquid Filling).

In filling the tanks during these tests, filters were not installed in the lines connecting the ammonia supply bottle to the propellant storage tank. While no serious difficulties were encountered during the testing directly attributable to the lack of filters it is recommended that they be installed in any fill system.

P.

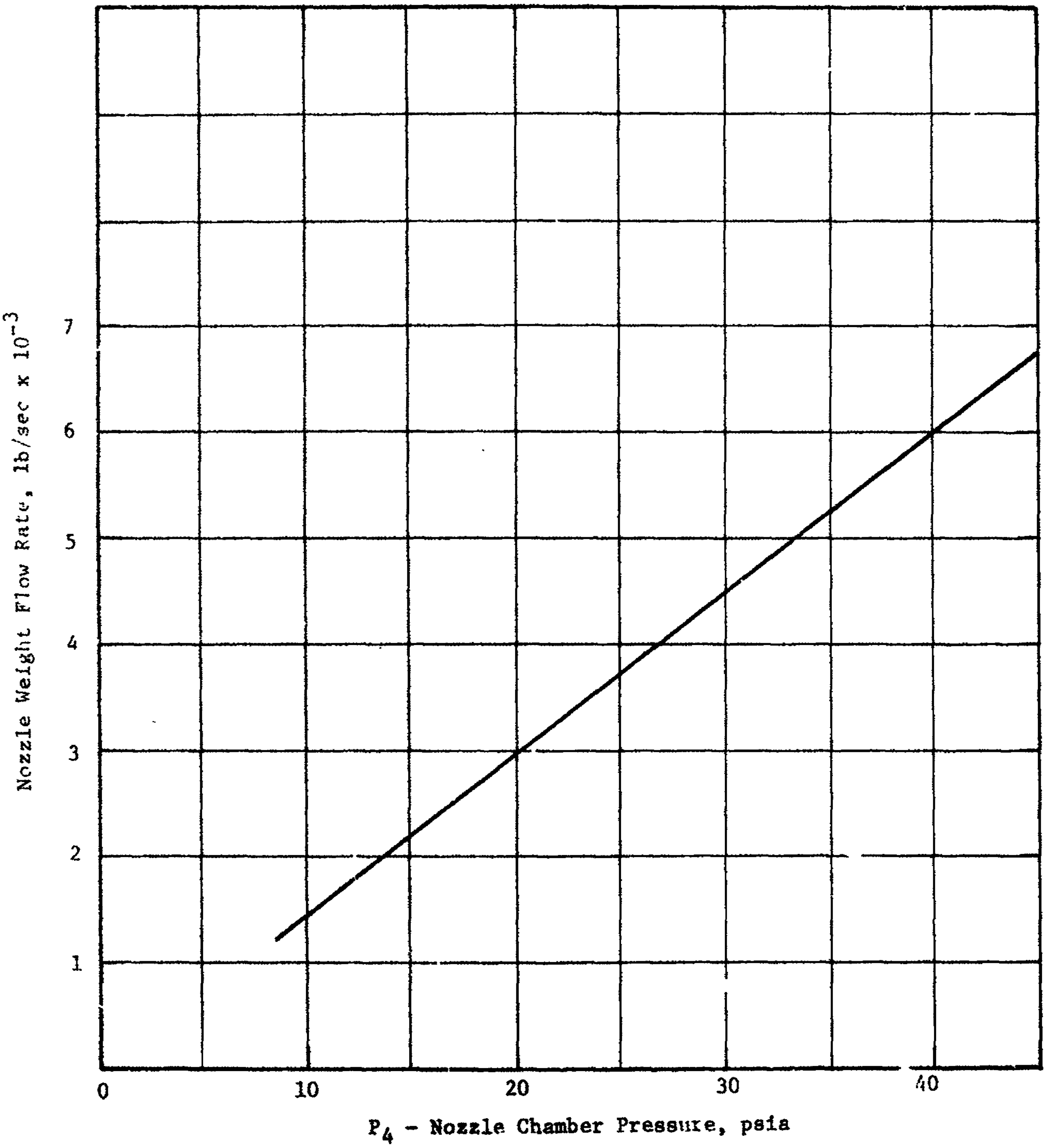


Figure 37. Nozzle Weight Flow Rate As A Function of Chamber Pressure (P_4).

Q.

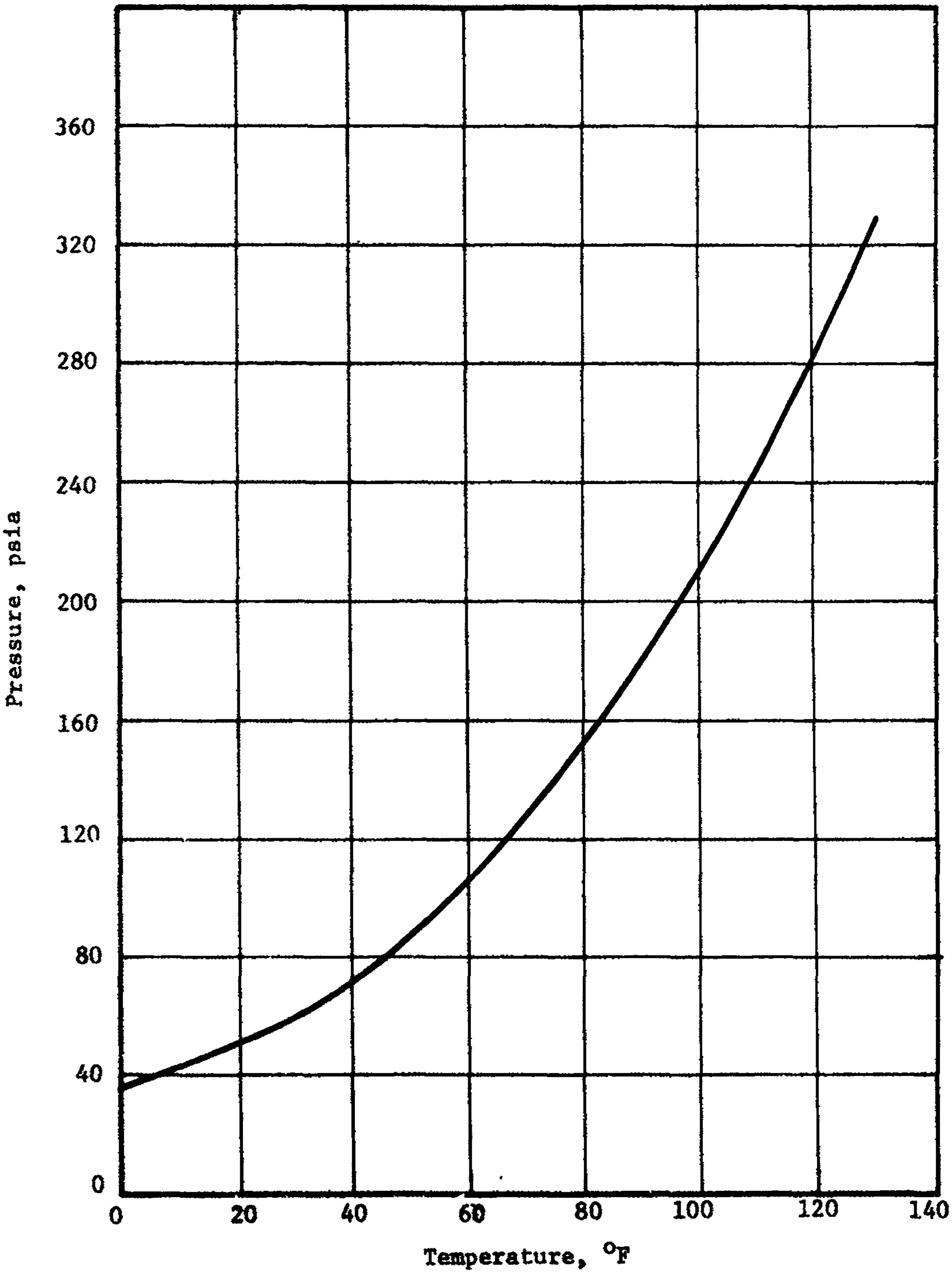


Figure 28. Vapor Pressure of Saturated Ammonia.

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APPENDIX A

COMPONENT AND ASSEMBLY CLEANING

GENERAL ELECTRIC SPACE POWER & PROPULSION SECTION CINCINNATI, OHIO 45215	SPECIFICATION NO. 03-0050-00-A
ENGINEERING SPECIFICATION	DATE 27 July 1966

TITLE	ORIGINAL CONTRACT
COMPONENT AND ASSEMBLY CLEANING	

PREPARED BY: S. R. Thompson DATE 8/2/66

APPROVED BY: W R Young DATE 9/20/66

APPROVED BY: WH Townsend DATE 10/14/66

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SUPERSEDES SPECIFICATION NO.	DATED	SEE SPPS INSTRUCTIONS SERIES 03.106

SP 1096

1. SCOPE

1.1. Scope. This specification establishes procedures and material processes for cleaning, handling and packaging of contamination controlled items. Ref· ·ce to this specification shall be made on engineering drawings whenever applicable. .nformation or requirements on such drawings supersede this specification.

2. APPLICABLE DOCUMENTS

2.1. Government Documents

L-P-378a 10 August 1960 (and amendments)	Plastic Film
MIL-P-27401B 19 September 1962	Nitrogen, Propellant Pressurizing Agent
BB-N-411 10 September 1964 (and amendments)	Nitrogen Technical, Type I, Class I, Grade A
MIL-F-5566	Isopropyl Alcohol
MSFC-Spec. 237A 16 October 1964	Freon TF, Precision Cleaning Agent (PCA)

2.2. Non-Government Documents

ARP-598 1 March 1960	Procedure for the Determination of Particulate Contamination of Hydraulic Fluids by the Particle Count Method
ARP-743 1 February 1963	Procedure for the Determination of Particulate Contamination of Air in Dust Controlled Spac·s by the Particle Count Method.
ADM-30 1965	(Millipore Filter Corp.) Detection and Analysis of Contamination
ADM-60 1963	(Millipore Filter Corp.) Ultracleaning of Fluids and Systems
SPPS Spec. #03-0049-00-A July 1966	Contamination Con.rol Area Facilities

3. REQUIREMENTS

3.1. Equipment and Apparatus

3.1.1. Millipore Filter Corporation

3.1.1.1. Gas Line Filter Holders - XX40-025-00

3.1.1.2. Aerosol Standard Filter Holder - XX50-047-00

3.1.1.3. Limiting Orifices, 0.5, 1.0, 3.0, 4.9, 10.0 liters/min. - XX50-000-00

3.1.1.4. Pyrex Microanalysis Filter Holders - XX10-025-00

3.1.1.5. Solvent Filtering Dispensers - XX66-025-00

3.1.1.6. Petri Dishes, plastic disposable PD10-047-00

3.1.1.7. Vacuum-Pressure Pump - XX60-000-00

3.1.1.8. Binocular Microscope and associated accessories - XX75-000-00

3.1.1.9. Pyrex Filter Holders - XX10-047-00

3.1.1.10. Hydrosol Stainless Filter Holder - XX20-047-20

3.1.1.11. Field Monitors - MAWG037PO

3.1.1.12. Filters

3.1.1.12.1. RAWG-025-00 1.2 micron, pore size

3.1.1.12.2. AAWG-047-00 0.8 micron, pore size

3.1.1.12.3. AABG-047-00 0.8 micron, pore size

3.1.1.12.4. HAWG-047-00 0.45 micron, pore size

3.1.1.12.5. HABG-047-00 0.45 micron, pore size

3.1.1.12.6. HAWP-047-00 0.45 micron, pore size

3.1.2. Gelman Corporation

3.1.2.1. Pressure-Volume Filter Holders

3.1.2.2. Filters

3.1.2.2.1. Metricel - GA3 5 micron pore size

3.1.2.2.2. Metricel - GA3 1.2 micron pore size

3.1.3. Ultraviolet Light Source - Model B100 Blak Ray (or equivalent)

3.1.4. Analytical Balance - Voland Model 340D (or equivalent)

3.1.5. Vacuum Oven - NAPCO Model 5830 (or equivalent)

3.1.6. Ultrasonic Agitation Equipment

3.1.6.1. For Intermediate Cleaning - Model G160 - National Ultrasonics Corporation.

3.1.6.2. For Final Cleaning - Model MFD-25-F - Branson Corporation.

3.1.7. Laminar Flow Modules

3.1.7.1. Model LF10 SP676 Baker Corporation

3.1.7.2. Model LF4421 SP675 Baker Corporation

3.1.8. Heat Sealer - Audion 580A

3.1.9. Vapor Degreaser - Detrex Model VS-800-S

3.1.10. Filtering Flasks - Heavy wall, with tubulation - 1000 ml.

3.1.11. Sampling Bottles - standard "milk dilution" bottles scribed at 99 ml.

3.1.12. "Saran" wrap or "Mylar"

3.1.13. Polyethylene bags and sheets - 0.005 in. thick or greater per L-P-378a.

3.2. Chemicals and Gases

3.2.1. Freon "TF", per MSFC237 (PCA)

3.2.2. Freon T-WD602

3.2.3. Isopropyl Alcohol, per MIL-F-5566

3.2.4. Deionized Water

3.2.5. Detergent - Bendix Corporation, DIRL-SOF-601

3.2.6. Dirl-Rinse

3.2.7. Nitrogen gas, per MIL-P-27401b

3.2.8. Nitrogen gas, per BB-N-411

3.2.9. Acetone, Reagent Grade

3.2.10. Ethyl Alcohol, Reagent Grade

3.2.11. Trichlorethylene, Reagent Grade

3.3. Materials Processing. Various materials shall be processed in accordance with the following table for optimization of contamination control.

Material	Process	Applicable Section (Paragraph)
1. Metallic Components	(a) Preclean	3.4.1.1. or 3.4.1.2.
	(b) Intermediate Clean	3.4.2.1. (Note)
	(c) Final Clean	3.4.3.1. and/or 3.4.3.2.
	(d) Visual Inspect	3.4.4.
	(e) Verify Cleanliness	4.3. and 4.5. (if required)
	(f) Package	5.1.

NOTE: Delete paragraph 3.4.2.1.3. for anodized aluminum components

Material	Process	Applicable Section (Paragraph)
2. Elastomers and Other Non-Metallics	(a) Clean	3.4.2.1. (Note)
	(b) Visual Inspect	3.4.4.
	(c) Package	5.1.

NOTE: Cleaning of non-metallics shall only be performed with the concurrence of the analytical chemist assigned to the Space Power and Propulsion Section Contamination Control Facility.

Material	Process	Applicable Section (Paragraph)
3. Materials with special surface treatments (cadmium plating, etc.)	(a) Preclean	3.4.1.2.
	(b) Final Clean	3.4.3.2.
	(c) Visual Inspect	3.4.4.
	(d) Verify Cleanliness	4.3. and 4.5, (if required)
	(e) Package	5.1.

3.4. Cleaning Processes and Procedures

3.4.1. Precleaning. All parts shall be visually examined, before entering the contamination control area, for undesirable or excessive contamination on their surfaces. If such contamination exists, appropriate treatments (pickling, vapor honing) shall be used for removal. These treatments and following precleaning treatments shall be conducted external to the control area.

3.4.1.1. Vapor Degreasing of Machined Parts. All machined metallic parts, excepting those with special surface treatments, shall be degreased in trichlorethylene vapor as follows:

3.4.1.1.1. Position parts in a basket or rack which will permit maximum drainage.

3.4.1.1.2. Lower parts into the vapor. They shall remain in the vapor until condensation on their surfaces stops. Parts shall be rotated to insure maximum cleaning action. A degreasing spray lance should be used on parts containing recesses and/or cavities.

3.4.1.1.3. Slowly remove the basket or rack from the degreasing tank and allow parts to drain and dry.

3.4.1.2. Cold Degreasing. Selected metallic parts shall be precleaned by rinsing in a suitable solvent, such as trichlorethylene, acetone or Freon TF. Ultrasonic agitation will considerably enhance this cleaning operation, when part make-up permits. Brushing and scrubbing may be required to remove certain contamination.

Nylon bristle brushes and/or lint free cloths shall be used in this process. After degreasing, parts shall be allowed to dry.

3.4.1.3. Transportation into Contamination Control Area. After precleaning, all parts shall be placed in visually clean polyethylene bags, per L-P-378a, or covered containers for transportation into the control area.

3.4.2. Intermediate Cleaning. This step in the processing shall be used primarily to prepare parts for final cleaning to specified levels. However, due to the configuration or cleanliness requirements for particular components the steps described as follows may serve as a final cleaning operation; hence, in these cases, only a determination of the component cleanliness will be required after such processing.

All parts shall be handled, from this stage in the processing to final packaging with lint free gloves or by mechanical means such as tongs, tweezers, etc.

3.4.2.1. Ultrasonic Cleaning (Detergent-Deionized Water Solution). This cleaning treatment shall be conducted at room temperature. Power to the ultrasonic transducer shall be adjusted to attain optimum solution activity during the operation. The filtration system to the ultrasonic tank shall be "blanked off" during agitation to attain maximum cleaning effects. Parts which have special surface treatments shall not be ultrasonically agitated, since this treatment would tend to damage the prepared surfaces.

3.4.2.1.1. Solution shall be mixed at a proportion of 5 ounces detergent per gallon of deionized water. The rinse tank shall contain deionized water, to which has been added 4 ounces of Dirl-Rinse per gallon of water.

3.4.2.1.2. All aluminum parts shall be segregated from others before cleaning, since different processing is required. Aluminum components shall be submerged in the ultrasonic detergent solution for a maximum of 5 minutes, with medium solution activity.

3.4.2.1.3. Stainless steel and most other metallic components shall be similarly submerged in the detergent solution for time intervals up to 30 minutes, using maximum solution activity.

3.4.2.1.4. After ultrasonic agitation treatment has been completed, parts shall be placed in the rinse tank for 5 to 10 minutes, using mechanical agitation to assist in rinsing action.

3.4.2.1.5. Parts shall be rinsed with filtered deionized water over the laboratory sink. The water is filtered through a 5 micron prefilter and a 1.2 micron final filter. The filters shall be changed on a weekly basis during normal working periods.

3.4.2.1.6. Parts shall be finally rinsed with filtered isopropyl alcohol, per MIL-F-5566, dispensed from a solvent filtering dispenser. The alcohol shall be filtered by passing through a 1.2 micron filter encased in the dispenser bottle. This filter shall be changed on a weekly basis or as required to obtain sufficient flow.

3.4.2.1.7. The parts shall then be dried by placing them in a stream of dry, filtered (1.2 micron) nitrogen, per BB-N-411. Parts shall be stored in visually clean polyethylene bags, per L-P-378a, if final cleaning operation does not immediately follow.

3.4.3. Final Cleaning. All processing described in this section shall be conducted within the working spaces of the laminar flow clean modules. All equipment used shall be cleaned in accordance with specification SPPS 03-0049-00-A.

3.4.3.1. Ultrasonic Cleaning - Freon TF SPEC 237 (Precision Cleaning Agent). The ultrasonic equipment shall be the vapor-rinse system contained within one of the permanent ultraclean benches.

3.4.3.1.1. Before parts or assemblies are cleaned in the ultrasonic Freon TF system, they shall have been processed through the appropriate procedures outlined in Sections 3.4.1. and 3.4.2.

3.4.3.1.2. Parts shall be placed on hooks or in a basket to allow for maximum drainage, lowered into the vapor and held there until condensation on parts ceases.

3.4.3.1.3. Work shall be transferred to sonic reservoir and power to ultrasonic transducer turned on and adjusted to obtain optimum activity. Parts should remain in reservoir for a minimum of 5 minutes. Parts shall be repositioned in reservoir, as required, to eliminate air locks and insure maximum cleaning action.

3.4.3.1.4. Parts shall be returned to vapor rinse tank and held again until condensation stops. Slowly remove parts from vapor side and allow to dry.

3.4.3.1.5. Alternate Ultrasonic Cleaning Method using Freon TF (PCA). This method shall be used for cleaning larger components which will not fit within the tank of the ultrasonic vapor-rinse system.

3.4.3.1.5.1. Components shall be placed in a container which has been precleaned and flushed with ultraclean Freon TF. Sufficient Freon TF (filtered through a 0.45 micron filter) shall be added to envelop parts and the container covered.

3.4.3.1.5.2. Entire container shall be inserted in ultrasonic tank used for intermediate cleaning. (NOTE). Tank should be filled with a convenient fluid for transmission of sonic waves. Apply energy to transducer for appropriate time interval.

NOTE: This tank shall be used because of larger capacity.

3.4.3.1.5.3. Container shall be removed, excess fluid drained from its exterior, and allowed to dry. After drying, container shall be returned to laminar flow bench, opened and cleaned component removed. Sample of Freon TF used, shall be taken and saved for later determination of sample cleanliness. Sampling techniques shall be in accordance with procedures indicated in ADM 30 and ADM 60 (Millipore).

3.4.3.2. Flushing (Freon TF - Precision Cleaning Agent). This process shall be used for final cleaning of parts that would not lend themselves to the ultrasonic Freon TF system due to size or material considerations.

3.4.3.2.1. No parts are to be flushed unless they have been processed through the appropriate procedures indicated in Sections 3.4.1. and 3.4.2.

3.4.3.[illegible] . Freon TF used for flushing shall have passed through a 0.45 micron filter. A solvent filtering dispenser shall be used for flushing small parts; whereas, larger parts shall be flushed with Freon supplied from a precleaned apparatus (apparatus cleaned and flushed with filtered Freon TF).

3.4.3.2.3. Parts shall be flushed individually by holding them with forceps, etc., or placing them in a basket and inserting the basket into a catch basin. This will normally depend on the size and/or complexity of the parts involved.

3.4.3.2.4. Protective measures shall be taken when flushing and handling parts to insure that neither dry skin particles or skin oils enter the flushing system or parts being flushed.

3.4.3.2.5. Adequate means shall be taken to insure that all parts are thoroughly flushed.

3.4.3.2.6. Parts shall be dried after flushing by placing them in a stream of dry filtered (1.2 micron) nitrogen.

3.4.4. Visual and Ultraviolet Light Inspection.

3.4.4.1. Visual Inspection. All parts shall be inspected by unaided eye for the presence of foreign matter, etc., on all accessible surfaces. Particles larger than 50 microns in size may be detected by this method.

3.4.4.1.1. Lighting shall be of sufficient intensity to maintain 50 foot-candles on all surfaces being inspected.

3.4.4.1.2. Special devices shall be used to assist in the inspection of inaccessible surfaces, as dictated by the application.

3.4.4.2. Ultraviolet Light Inspection. All parts shall be examined for the presence of petroleum type hydrocarbons and fluorescent particles by visual inspection methods with the aid of an ultraviolet lamp.

3.4.4.2.1. The area where this inspection shall take place must be capable of being completely blacked-out (absence of white light).

3.4.4.3. Recleaning. If either the visual or ultraviolet light inspection tests indicate unacceptable foreign matter, parts shall be recleaned.

4. QUALITY ASSURANCE PROVISIONS

The following sections describe procedures for 1) verification of air particulate contamination in the control area, 2) verification of cleanliness levels of final rinse test fluids, 3) determination of cleanliness levels and non-volatile residues associated with cleaned components, and 4) indicate general cleanliness levels to be determined by using processes described in this specification.

4.1. Airborne Cleanliness Verification. A determination of the air particulate contamination within the control area shall be conducted on a weekly basis. The results of these tests shall be documented and maintained on record. The tests shall show that the area external to the laminar flow ultraclean modules meets Class 100,000 levels, while the modules shall meet Class 100 levels, as defined by Federal Standard #209.

4.1.1. General procedure to be followed for sampling and counting shall be in accordance with ARP (Aerospace Recommended Practice) 743, with the following exceptions:

4.1.1.1. Sampling shall be performed under normal working conditions, at predetermined areas, both within the laminar flow modules and in the contamination control area.

4.1.1.2. Sampling equipment shall be covered with clean polyethylene material for transportation from laminar flow bench, (where filter is initially placed in holder) to sampling area.

4.1.1.3. All counting of particle contamination shall be conducted on the laminar flow ultraclean benches.

4.1.1.4. Only a qualitative determination of the acceptability of the laminar flow modules may be made by following the indicated practice (ARP-743), since the smallest particle that may be counted by this technique is 5 microns in size and compliance with Federal Standard #209 dictates that no particles larger than 4 microns in size (per cubic foot of air) shall be determined and still meet Class 100 requirements. Therefore, examination of the filters used in checking the laminar flow modules shall show no particles 5 microns or larger in size; if none are detected the module shall be considered as Class 100 and acceptable for usage.

4.2. Cleanliness Level Verification of Final Flush Fluid. A determination of the particulate contamination in the solvents used for final cleaning, flushing, etc., shall be made daily using procedures indicated in ARP 598. Results of such tests shall be documented and maintained on record; copies of results should also accompany data sheets related to parts cleaned and checked for cleanliness on that day. All test solvents shall be passed through filters, whose pore sizes range from 0.45 to 1.2 microns; before being sampled or before being passed over parts to be sampled. The maximum particle count of the final flush fluid sample shall be no greater than 10% of the allowable particulate contamination for parts being cleaned. The cleanliness of parts, processed per Section 3.4.3.1.5., shall be determined by measuring contamination levels existent in the Freon TF used.

4.3. Particulate Sampling of Cleaned Parts. All apparatus used shall be cleaned, per Section 3.3., and flushed with ultraclean Freon TF. The following procedure shall be used to determine the cleanliness of parts processed per Section 3.3.

4.3.1. Rinse parts with appropriate solvent (Freon TF for parts cleaned with Freon) which has been passed through a 0.45 micron pore size filter. Discard efflux liquid.

4.3.2. Place a filter (0.45 micron pore size) in the sampling apparatus between the fritted glass base and funnel.

4.3.3. Rinse part with additional solvent, prefiltered through a 0.45 micron filter, directly over pyrex filter funnel. If part does not lend itself to rinsing directly into funnel, efflux liquid may be collected in a clean glass beaker.

4.3.4. A minimum of 100 ml. of solvent per square foot of significant surface area shall be used, unless otherwise specified. If area is less than a square foot, it shall be treated as a square foot.

4.3.5. A note of caution should be interjected here: Exercise proper care in handling to insure against introduction of contamination from external sources (loose skin particles, lint, hair, etc.).

3

4.3.6. Apply vacuum to draw solvent through the filter. When filtration is 2/3 completed, release the vacuum, to allow some liquid to remain in the funnel. Carefully rinse down the walls of the funnel with ultraclean solvent. (Do not rinse filter surface directly, as this will upset the distribution of particles on the filter surface). Reapply vacuum until funnel is empty and filter is dry.

4.3.7. Turn off vacuum and remove clamp and funnel so that filter remains on fritted glass base.

4.3.8. Remove filter from base, using unserrated tipped forceps, and transfer to a clean petri dish, grid side up.

4.3.9. Conduct a particle count on the filter, using procedures indicated in ARP-598 and ARP-743, to determine if component has been satisfactorily cleaned.

4.3.10. When requirements dictate a non-volatile residue test, a blank test sample shall be drawn from the fresh solvent prior to flushing and the filter efflux remaining in the vacuum flask shall be retained for a comparative test after sampling.

4.4. Cleanliness Levels of Cleaned Parts. The cleanliness levels obtainable by using processes described in this specification are as shown in the following table.

Particle Size microns	Maximum Number of Particles/100 ml. of Solvent Passed Over Component Surfaces
10 - 25	160
25 - 40	40
40 - 80	20
>80	0
*80 -250 (Fibers)	0

Components or assemblies cleaned in accordance with this specification shall have no greater surface contamination than that indicated in the above table.

* Fibers larger than 80 microns shall be considered only when they appear in the background count of the test filter. If any such fibers, found after cleaning, were not initially present on the filter surface, subject parts shall be reprocessed.

4.5. Non-Volatile Residue (NVR) Determination. Non-volatile residue tests shall be conducted on the basis of 100 ml. of solvent per square foot of surface area, using the following procedure.

4.5.1. A blank or comparative sample of the unused solvent is required. It shall be obtained in a manner identical to that used to obtain the test sample, except that it shall not have passed over the parts being tested.

4.5.2. Transfer 100 ml. of solvents (blank and test sample) into clean dry beakers, evaporate to 10-20 ml.

4.5.3. Quantitatively transfer to constant weight (±0.1 mg. tared) weighing containers.

4.5.4. Continue evaporation to approximately 5 ml. Do not allow solvents to evaporate to dryness.

4.5.5. Place both containers in a constant temperature oven at 220-230°F hold for 1 hour at temperature.

4.5.6. Remove containers, cool and weigh to nearest 0.1 mg., repeat steps 4.5.5. and 4.5.6. to constant weight.

4.5.7. Subtract weights of containers in step 4.5.3., from weights of containers and residues in step 4.5.6.

4.5.8. Compare results obtained for both used and unused solvent. The difference in weights shall not be greater than 0.8 mg. The blank sample shall have a maximum NVR of 2 mg.

4.6. Filter Examination. The filters used for sampling of cleaned parts, shall be examined visually with the aid of an ultraviolet light, for the presence of hydrocarbons or other fluorescent particles. This inspection shall indicate no visible particles or fluorescence.

4.7. Rejection. Parts or assemblies which have not been processed in accordance with this specification shall be rejected unl   so dictated by superceding documents.

4.8. Reports. Reports which include all pertinent processing data and results of quality assurance testing, shall accompany cleaned components.

5. PREPARATION FOR DELIVERY

5.1. Packaging and Identification. Specific type of packaging shall normally be included with particular part specification. However, when such is not specified, the following shall apply.

5.1.1. After final inspection and before packaging, all components and assemblies shall be reinspected with an ultraviolet lamp, as per Section 3.4.4.2. Any fluorescent areas shall be wiped clean with a lint-free cloth, dampened with ultraclean Freon TF (PCA).

5.1.2. No plastic port closures shall be permitted.

5.1.3. Parts shall be wrapped in polyethylene sheeting (per L-P-378a) which has been cleaned appropriately with filtered (1.2 micron pore size) nitrogen, per specification MIL-P-27401b. The sheeting shall also have been inspected for fluorescence with the ultraviolet light. The sheeting shall be secured with Scotch Brand 471 White Plastic film (or equivalent).

5.1.4. The wrapped parts are then contained in two heat sealed polyethylene bags (per L-P-378a) with a tag between them, which indicates part identity and level of cleanliness of parts inside.

6. NOTES.

DEFINITIONS: Ultraclean Freon - Freon TF which has passed through a 0.45 micron pore size filter immediately before contact with surfaces being flushed or cleaned.

Fiber - A particle larger than 80 microns, with a length to width ratio greater than 10:1.

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APPENDIX B

CONTAMINATION CONTROL AREA FACILITIES

GENERAL ELECTRIC SPACE POWER & PROPULSION SECTION CINCINNATI, OHIO 45215	SPECIFICATION NO. 03-0049-00-A
ENGINEERING SPECIFICATION	DATE 26 July 1966

TITLE	ORIGINAL CONTRACT
CONTAMINATION CONTROL AREA FACILITIES	

PREPARED BY: S. R. Thompson DATE 8/20/66
S. R. Thompson

APPROVED BY: W. R. Young DATE 8-24-66

APPROVED BY: WH Townsend DATE 12-8-66

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ISSUED BY: D.A. Pritchett MAIL ZONE N-21 PHONE 3924/2438
DRAFTING

SUPERSEDES SPECIFICATION NO.	DATED	SEE SPPS INSTRUCTIONS SERIES 03.106

SP 1096

1. SCOPE

1.1. Scope. This specification describes the Space Power and Propulsion Section contamination control facilities and establishes the practices to be followed for maintenance of the area and equipment located therein. Reference to this specification shall be made on engineering drawings whenever applicable.

2. APPLICABLE DOCUMENTS

2.1. Government Documents

Federal Standard #209 16 December 1963	Clean Room and Work Station Requirements, Controlled Environment.

2.2. Non-Government Documents

ARP 598 March 1, 1960	Procedure for the Determination of Particulate Contamination of Hydraulic Fluids by the Particle Count Method.
ARP 743 February 1, 1963	Procedure for the Determination of Particulate Contamination of Air in Dust Controlled Spaces by the Particle Count Method.
ADM 30 1965	(Millipore Filter Corp.) Detection and Analysis of Contamination.
SPPS Spec. No. 03-0050-00-A July 1966	Component and Assembly Cleaning.

3. REQUIREMENTS

3.1. Clean Room Construction and Equipment Description. The "Clean Room" is a limited access contamination control area in which positive pressurized, filtered incoming air is supplied and which contains laminar flow ultraclean modules. The area external to the clean modules, within the clean room, shall be maintained at a class 100,000 level, per Federal Standard 209.

3.1.1. Laminar Flow Modules. All modules shall contain HEPA type absolute filters which are 99.97% effective at removing particles from the air stream 0.3 micron in size. All units shall meet class 100 contamination levels as defined by Federal Standard 209. Both portable and permanent type modules (benches) shall be available for use. One of the permanent modules shall contain an ultrasonic agitation unit.

3.1.2. Ultrasonic Agitation Equipment

3.1.2.1. Unit Used for Intermediate Cleaning. This unit shall have a 10 gallon ultrasonic tank and a 10 gallon rinse tank. Both tanks shall be connected to filters which will remove contaminants, 10 microns or larger in size, from the contained liquids. Both tanks shall be constructed of stainless steel.

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3.1.2.2. Unit Used for Final Cleaning Within Clean Bench. This unit (3.5 ft^3 volume) shall be an ultrasonic vapor-rinse system, continuously filtered, during operation, through a 1 micron filter. The tank shall be constructed of stainless steel.

3.1.3. Water, Gas and Vacuum Supplies. Deionized water, high pressure gas and vacuum sources shall be located external to the clean area and shall be brought into the area by means of stainless steel piping.

3.1.4. Air Supply. Incoming air to the control area shall be passed through a spun glass filter. A positive air pressure of 0.12 mm. Hg minimum (relative to external rooms) shall be maintained in the area.

3.1.5. Room, Furniture and Preparation

3.1.5.1. Chairs shall be constructed from non-abradable materials and shall have hard rubber wheels.

3.1.5.2. Working surfaces, excluding those within the laminar flow modules, shall be covered with Formica tops (one piece with rounded edges).

3.1.5.3. Sink in the room shall have an acid resistant top, bowl and piping.

3.1.5.4. Floor covering - Vinyl with limited seams.

3.1.5.5. Walls shall be painted with epoxy enamel.

3.1.5.6. All light fixtures shall be covered with sealed glass shields.

3.1.6. Other Equipment

3.1.6.1. Millipore analytical filtration and sampling apparatus.

3.1.6.2. Microscope - Binocular type with movable stage - 40X, 100X, 200X magnification with measuring eyepiece.

3.1.6.3. Ultraviolet Light - portable, 50-60 cycle, long wave, mercury quartz lamp.

3.1.6.4. Analytical Balance - capable of weight determinations to ± 0.0001 gm., 500 gm. total capacity.

3.1.6.5. Vacuum Oven - 1 ft^3 volume (optional).

3.1.6.6. Bag Sealer - for sealing thin polyethylene sheeting.

3.1.6.7. External-Internal "intercom" system.

3.1.6.8. Positive air lock window with glove ports for inspection of parts (optional).

3.2. Clean Room Regulations

3.2.1. Only authorized personnel, directly concerned with cleaning, testing, fabrication and quality control of parts within, shall be permitted within the area (room). Authorized personnel shall be designated by the clean room supervisor.

3.2.2. Traffic into and out of the area shall be kept at a minimum. Communications with personnel working inside shall be made through the use of the "intercom" system.

3.2.3. Personnel entering the room shall wipe their shoes, on a floor mat provided, before entering the room. Immediately after entering the room, plastic booties shall be placed on shoes.

3.2.4. Only "Vellum" paper shall be used in the Clean area; minimum quantities shall be used

3.2.5. All test fixtures, tools, monitoring equipment, etc., required in the clean area shall be free from oil, grease and other obvious contamination. All tooling, etc. used shall be removed from the room at the completion of associated operations.

3.2.6. Gas supply, incoming deionized water, and vacuum lines shall be fabricated from Type 300 series stainless steel whenever possible. No high pressure gas bottles, vacuum sources, or water purification equipment shall be permitted within the clean room.

3.2.7. Chemicals required for the various cleaning operations shall be carried into the control area as required, maintaining the quantities therein at a minimum. Reserve supplies of these chemicals shall be stored external to the clean room.

3.2.8. No abrasive materials, such as sandpaper, lapping compounds, etc., nor any abrading operations shall be permitted in the clean room. Cotton swabs shall not be used in the room at any time.

3.2.9. The floors in the room shall be mopped weekly with a free-rinsing detergent solution. All bench tops, walls, and ledges (excluding laminar flow benches) shall be wiped weekly with a damp lint-free cloth.

3.2.10. Smoking, eating, and drinking are prohibited within the clean room <u>at any time</u>.

3.3. <u>Maintenance and Control of Laminar Flow Modules</u>. In general, the use of the laminar flow modules shall require more strigent controls, than the surrounding areas in the clean room, to maintain maximum cleanliness.

3.3.1. The laminar flow benches shall be used primarily for the following operations:

3.3.1.1. Final flushing, ultrasonic agitation and cleaning of parts.(Note).

3.3.1.2. The assembly and testing of cleaned parts.

3.3.1.3. The particulate counting of air contamination and hydraulic contamination samples.

NOTE: One laminar flow bench contains ultrasonic agitation equipment as an integral part of the unit.

3.3.2. All personnel working in the clean room and within the portable laminar flow clean modules shall wear lint free head covers, boots and smocks. All of these garments shall be changed on a weekly basis, minimum.

3.3.3. The working surfaces of the ultraclean modules shall be wiped daily with a lint-free cloth, saturated with a suitable solvent which has been ultracleaned. Equipment located within the benches shall be similarly cleaned on a daily basis.

3.3.4. No paper shall be permitted within the working areas of the clean modules.

4. QUALITY ASSURANCE PROVISIONS

4.1. Airborne Cleanliness Verification. A determination of the air particulate contamination within the control area shall be conducted on a weekly basis; using procedures indicated in ARP 743. These tests shall show that the area external to the ultraclean laminar flow modules meets class 100,000 level, while the modules shall meet class 100 levels, as defined by Federal Standard 209. The results of such tests shall be documented and maintained on record. If indicated cleanliness levels are not observed, appropriate measures (changing of filters in laminar flow modules, recleaning of floors and walls, etc.) shall be taken to alleviate the condition.

4.2. Ultrasonic Fluids Cleanliness Verification. Following procedures indicated in ARP 598 the fluid in the ultrasonic agitation unit, used for final cleaning, shall be tested weekly to establish time of change for the filtering elements. This testing shall be conducted as required, but on a weekly basis as a minimum. The maximum particle count from such tests shall be no greater than 10% of the allowable particle contamination of parts to be cleaned in this unit. If counts of greater than 10% are observed, filtering elements shall be changed and the cleanliness of the fluid reverified before the unit shall be considered ready for parts cleaning.

4.3. Ultraviolet Light Inspection. The contamination control area shall be inspected by means of an ultraviolet lamp, under completely blacked-out conditions. This inspection shall be conducted immediately after daily and/or weekly cleaning. The presence of hydrocarbons, as indicated by this inspection, shall necessitate recleaning and reinspection until none are observed. All tooling, etc. shall be similarly inspected before use and recleaned, if necessary.

5. PREPARATION FOR DELIVERY. Not applicable.

6. NOTES. None

7. DEFINITION. Ultraclean solvent - A solvent which has passed through a 0.45 micron filter before being used. Filter located at last possible point in supply line.